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# ASTROGEOLOGIC STUDIES

## ANNUAL PROGRESS REPORT

July 1, 1963 to July 1, 1964

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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

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ANNUAL PROGRESS REPORT

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PART C: COSMIC CHEMISTRY AND PETROLOGY

November 1964

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DEPARTMENT OF THE INTERIOR  
UNITED STATES GEOLOGICAL SURVEY



# CONTENTS

	Page
PART C--COSMIC CHEMISTRY AND PETROLOGY	
Introduction-----	v
A spalled aerodynamically modified moldavite from	
Slavice, Moravia, Czechoslovakia, by E. C. T. Chao-----	1
Introduction-----	1
Evidence of spalling and aerodynamic ablation-----	2
Discussion-----	7
Acknowledgments-----	8
References-----	8
Some geologic occurrences of Australasian tektites,	
by E. C. T. Chao-----	10
Introduction-----	10
Sites near Manila and on Anda Island, Philippines-----	14
The Dalat sites of South Viet Nam-----	24
Sites on the Korat Plateau, Northeast Thailand-----	31
The Sangiran Dome sites of Java-----	46
The Port Campbell and Stanhope Bay sites of	
Victoria, Australia-----	52
Comparison of the geologic age with K/Ar age	
of Australasian tektites-----	55
The problems of estimating the density of	
fall of tektites-----	57

## CONTENTS--Continued

	Page
Source of tektites-----	60
Acknowledgments-----	60
References-----	62
The chemical composition of selected indochinites	
and philippinites, by Frank Cuttitta, E. C. T. Chao,	
and M. K. Carron-----	65
Introduction-----	65
Chemical composition of selected Australasian	
tektites-----	70
Conclusions-----	74
References-----	75
A comparison of two solution techniques used in	
emission spectroscopy: the gas controlled arc	
and rotating disc-high voltage spark, by	
Charles Annell-----	76
Introduction-----	76
Analytical techniques-----	76
Comparison of the two methods-----	78
Conclusions-----	84
References-----	84

# CONTENTS--Continued

	Page
Quantitative spectrographic determination of Na and K in silicate rock solutions using the rotating disc and high voltage spark, by Charles Annell-----	86
Introduction-----	86
New analytical procedure-----	87
Results-----	88
References-----	88
New compositional data on metallic spherules found in Philippine tektites, by F. C. Cuttitta, E. C. T. Chao, and Charles Annell-----	92
Introduction-----	92
Emission spectroscopic analysis-----	93
Neutron activation analyses-----	95
Acknowledgment-----	96
References-----	96
Some alkali and titania analyses of tektites before and after G-1 precision monitoring, by D. B. Tatlock-----	97
References-----	106

## CONTENTS--Continued

	Page
Luminescence of enstatite achondrite meteorites, by M. B. Duke and B. A. Tryba-----	110
Introduction-----	110
Red luminescence in the Norton County meteorite-----	111
Electron excitation of synthetic diopside-----	112
Discussion-----	112
References-----	113

## INTRODUCTION

This Annual Report is the fifth of a series describing the results of research conducted by the U.S. Geological Survey on behalf of the National Aeronautics and Space Administration. This report, which covers the period July 1, 1963 to July 1, 1964, is in three volumes corresponding to three main areas of research: Part A, Lunar and Planetary Investigations; Part B, Crater and Solid State Investigations; and Part C, Cosmic Chemistry and Petrology; and a map supplement. An additional <sup>12</sup> volume presents in abstract form summaries of the papers in Parts A, B, and C.

The major long-range objectives of the astrogeologic studies program are to determine and map the stratigraphy and structure of the Moon's crust, to work out from these the sequence of events that led to the present condition of the Moon's surface, and to determine the processes by which these events took place. Work being carried out that leads toward these objectives includes a program of lunar geologic mapping; studies on the discrimination of geologic materials on the lunar surface by their photometric, polarimetric, and infrared properties; field studies of structures of impact, explosive, and volcanic origin; laboratory studies on the behavior of rocks and minerals subjected to shock; and study of the chemical, petrographic and physical properties of materials of possible lunar origin and the development of special techniques for their analysis.

Part A: Lunar and Planetary Investigations contains (with the map supplement), the preliminary results of detailed geologic mapping on a 1:1,000,000 scale of five new quadrangles in the equatorial belt of the Moon. Several major stratigraphic units in the Imbrian and pre-Imbrian systems are described by the authors who have studied these quadrangles. Four papers discuss problems of origin and evolution of various types of craters and features associated with the craters such as rilles and rays. As a part of the lunar geologic investigations, detailed studies of the infrared emission and reflected visible radiation from the Moon are in progress; a description of a systematic program of photoelectric and photographic photometry and the relation of the visible lunar photometric function to the infrared emission are given in this report.

Part B: Crater Investigations contains the results of field and laboratory studies of shock and crater phenomenology. The effect of shock on rock materials forms the subject of four reports: (1) the shock wave synthesis of stishovite, (2) the physical properties of shock-formed plagioclase from a meteorite, (3) some characteristics of natural glasses and high pressure phases that serve as evidence for their origin by meteorite impact, and (4) the effect of shock on the radiogenic argon content of granite. One report concerns the shock equation of state on two rocks from Meteor Crater, Arizona. Two reports deal with experimental craters: one is concerned with a field study of craters formed by missile

impact and the other with a study of craters formed in porous-cohesive targets by hypervelocity projectiles. Work on three naturally formed craters is reported. This includes a new topographic map of Meteor Crater, Arizona, made to serve as a base for the geologic work; a geologic study of a meteorite crater and associated rays of ejecta at Henbury, Australia; and field and laboratory studies of the Flynn Creek structure, Tennessee.

Part C: Cosmic Chemistry and Petrology includes reports on <sup>16267</sup>aero-dynamic features, geologic occurrences, chemical composition and metallic spherules of tektites, methods of chemical analysis of tektites and other extraterrestrial material, and the luminescence of achondritic meteorites.

Author

# A SPALLED AERODYNAMICALLY MODIFIED MOLDAVITE

FROM SLAVICE, MORAVIA, CZECHOSLOVAKIA

by E. C. T. Chao

## Introduction

During a visit to moldavite localities in Bohemia and Moravia in Czechoslovakia in March and April of 1964, the author had the opportunity of inspecting more than 15,000 moldavite specimens. The main purpose of this inspection was to uncover moldavites which show evidence of aerodynamic ablation and moldavites which may contain various types of inclusions. Most of the specimens are deposited at the National Museum in Prague; about 3,500 belong to the private collection of Dr. Jan Oswald of České Budejovice and 500 to Mr. Josif Prokopec of České Krumlov. A small number of moldavites inspected belong to the Charles University and other private collectors.

The moldavites inspected have a wide variety of shapes. Many are of teardrop shape. A few are rod shaped and disc shaped, and a few are curved plates. Dumbbell-shaped and core-shaped ones are rare but have been observed. A very large fraction of the specimens inspected are fragments, mostly platy and some subrounded. The striking thing about the assortment and frequency of shapes of the moldavites is that they are very similar to those of Thailand and Indochina.



Among the large number of specimens inspected, none shows direct evidence of aerodynamic ablation. The moldavite described in this paper is the only specimen which shows indirect evidence of aerodynamic ablation. It is a large teardrop-shaped moldavite collected by Mr. Jaromir Šofr of Třebíč from a plowed field in an area of moldavite-bearing gravel adjoining the west side of the village Slavice in Moravia. It is greenish brown, translucent, measures 67 mm long, 33 mm wide, and 30 mm thick at the maximum cross section, perpendicular to the long axis, and weighs 64.75 grams. Except near the tip of the teardrop, which is slightly chipped in two places, the gross teardrop shape is well preserved.

#### Evidence of spalling and aerodynamic ablation

The profile is best observed with the specimen lying on its side (fig. 1a, lower left and lower right). The highly convex anterior side (fig. 1a, upper left, lower left and lower right) is covered with both deep and shallow pits of corrosive origin<sup>1/</sup>. Locally, the flow structure or schlieren is revealed in and across the pits. The plano-convex posterior side is relatively smooth (fig. 1a, upper right) and well preserved, in spite of the fact that crescent-shaped percussion marks are locally present, indicating erosion during transport in running water.

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<sup>1/</sup> See following page.

1/ F. E. Suess (1900) described in detail the sculpture of moldavites and interpreted the various highly polished intricate patterns of pits and grooves on them as of aerodynamic origin. Although the detailed mode of formation of such sculptures is not clearly known in all cases, the author has observed identical sculptures in philippinites, indochinites, and Thailand tektites where the sculptures were formed subsequent to rounding of the specimen by transport in terrestrial water bodies. Similar intricate sculpture on moldavites examined by the author also has a late history, that is, the sculpture was formed after the tektite fell. It is considered to be of corrosion origin, in agreement with the independent study of Professor Rudolf Rost of Charles University (oral communication, April 1964).

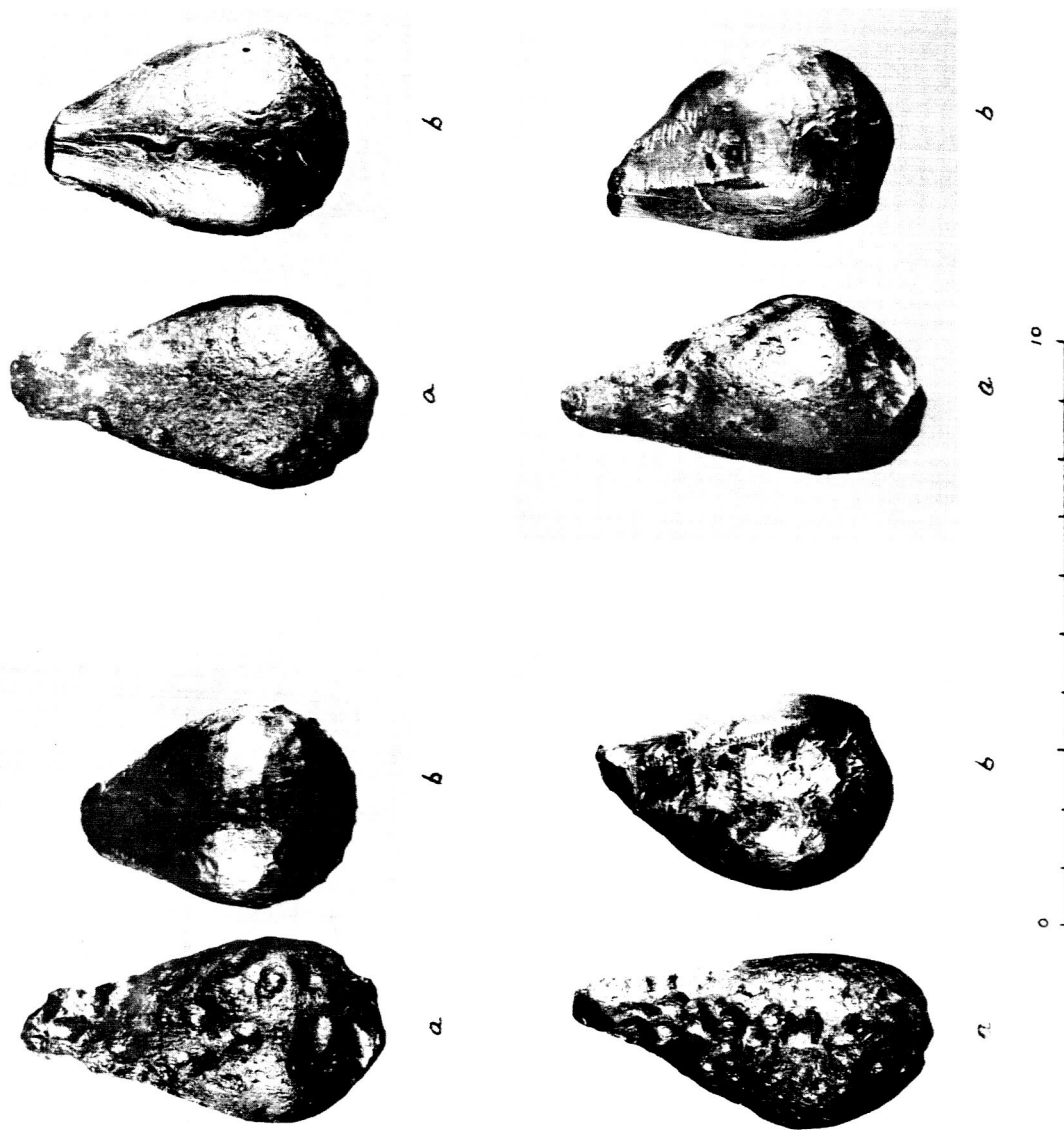


Figure 1. Comparison of spalled moldavite teardrop from Slavice, Moravia (a) with spalled australite teardrop from Renmark, South Australia (b). Upper right--posterior view; upper left--anterior view; lower right--side view with posterior side to the right; and lower left--side view with posterior side to the left.

The break in the curvature between the plano-convex posterior part and the strongly convex anterior portion (the keel) is indicative of spalling of the tektite. The keel is locally well preserved (fig. 1a, lower left), but elsewhere is not sharply defined. For comparison, an ablated and spalled large australite teardrop is shown (fig. 1b).

In australites, flaked cores, boats, dumbbells and flanged buttons show various stages of spalling as represented by specimens which partially retain the ablated front and side surfaces. These are known as "indicators" (Fenner, 1935; Baker, 1959). Figure 2a shows an indicator of an australite button with most of the anterior portion spalled off, leaving a conspicuous keel. As shown by the ring waves on the remnant unspalled piece, it is clear that spalling of the aerothermal stress shell did take place. A complete spalling of this aerothermal stress shell formed by secondary reheating and aerodynamic ablation results in a core as shown in figure 2b. Similarly an indicator of a partly spalled dumbbell (fig. 3b) demonstrates how a spalled dumbbell-shaped australite (fig. 3a) was derived. The formation of a core as a result of the spalling off of the aerothermal stress layer of the anterior and girdle area of an ablated australite and other Australasian tektite specimens has been experimentally demonstrated in detail by Dean R. Chapman (1964). There is no uncertainty concerning the derivation of these spalled tektites, although the primary aerodynamic ablation evidence has been completely removed.

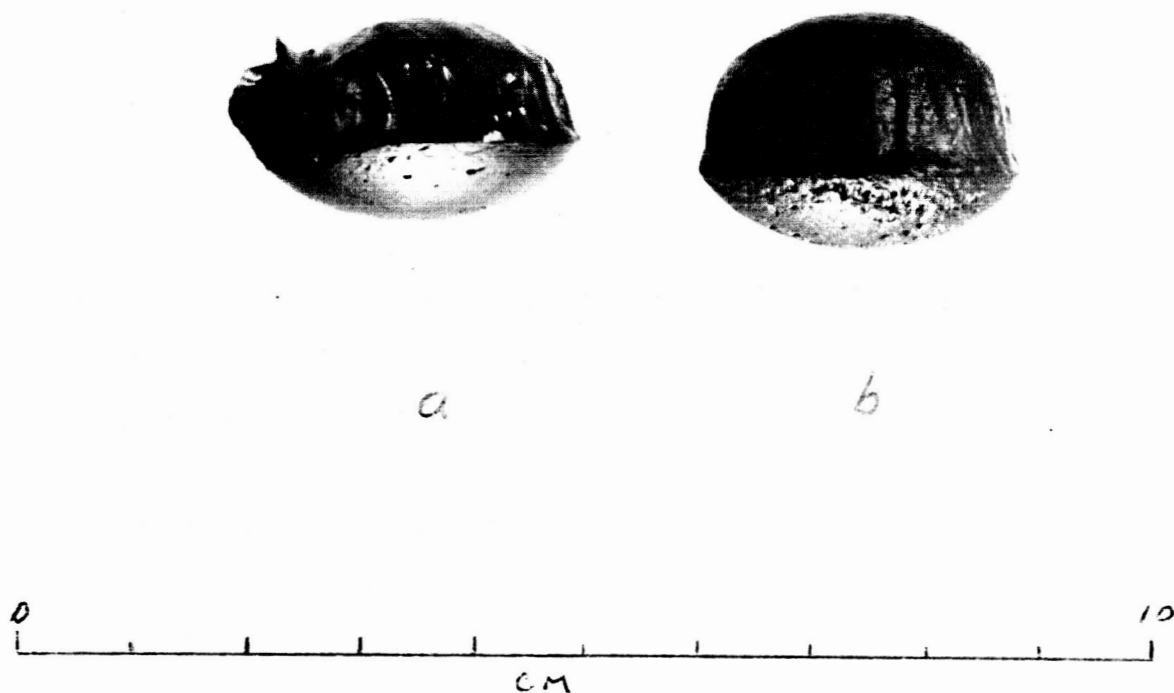


Figure 2. Photograph showing the partially spalled "indicator" core of an australite (a) from Charlotte Waters, N. T. Australia. Ring waves on the remnant unspalled portion are clearly visible. A spalled core with the aerothermal shell completely removed is shown on the right (b) from Hampton Hills, Kalgoorlie, W. Australia.

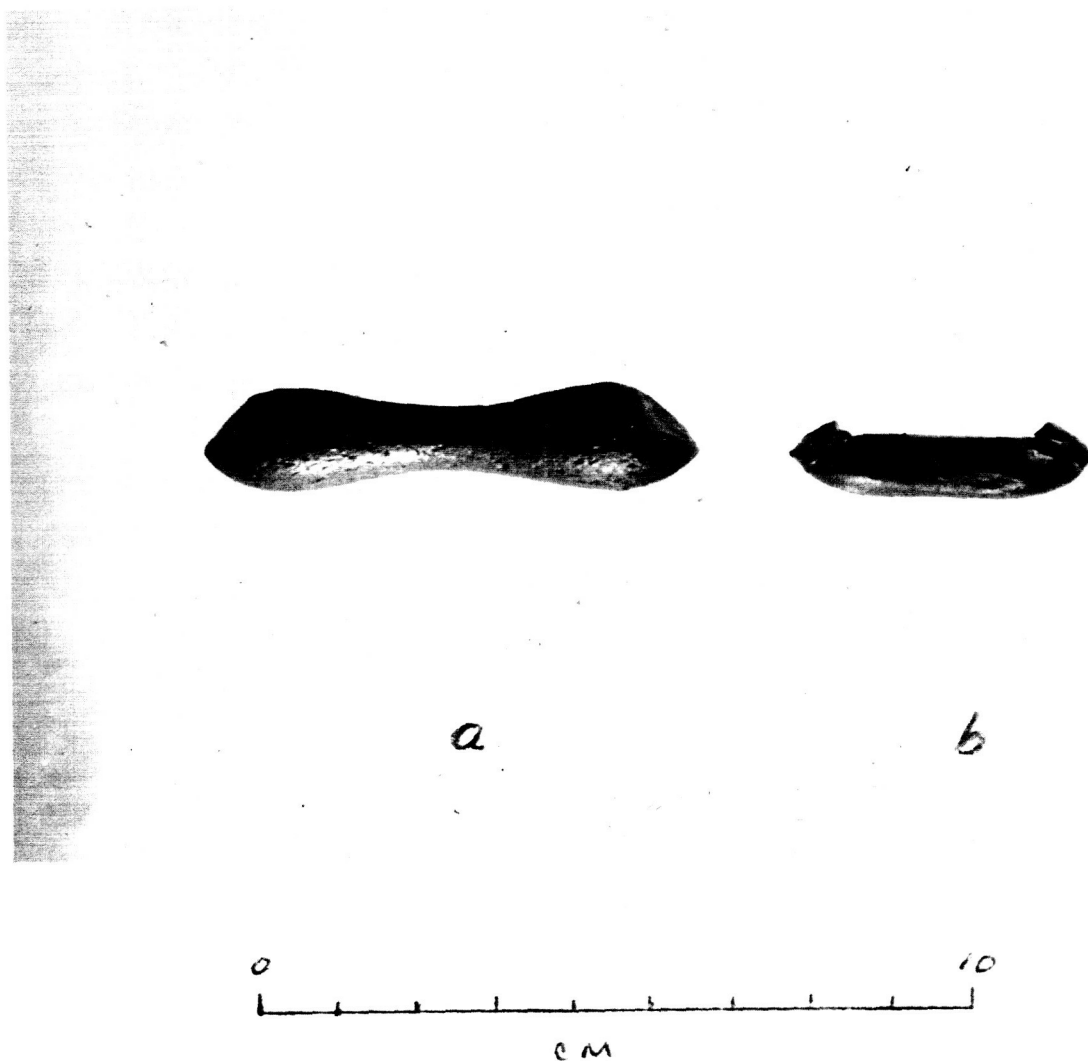


Figure 3. Photograph showing a spalled dumbbell with the aerothermal shell completely removed (a) from Hampton Hills, Kalgoorlie, W. Australia. An "indicator" dumbbell with remnant aerothermal stress shell is shown on the right (b), Hampton Hills, Kalgoorlie, W. Australia.

It is concluded that the spalled australite teardrop (fig. 1b) and the spalled moldavite (fig. 1a) were derived in the same manner, with a history of aerodynamic heating and ablation.

### Discussion

The large teardrop-shaped moldavite provides, in the author's opinion, the first tangible evidence that moldavites suffered aerodynamic heating and ablation of the anterior face during a second period of melting upon entry into the Earth's atmosphere. It must have entered the atmosphere as a cold glass body, probably at velocities greater than 5 kilometers per second. No ablation will occur on tektites with entry velocity less than 5 kilometers per second (Chapman and Larson, 1963).

Chapman and Larson (1963, p. 4340-4342) have argued against the terrestrial impact origin of australites from the aerodynamics point of view. They point out that in order for molten blobs of fused earth to fly unmolested by aerodynamic forces at shallow exit angles as small as 12 degrees, a relatively high vacuum of less than  $2 \times 10^{-7}$  atmospheres must exist in an area of 500 kilometers radius. The large teardrop-shaped moldavite from Slavice of Moravia was aerodynamically heated and perhaps ablated, requiring the presence of the atmosphere over the Bohemian and Moravian tektite strewnfield, less than 400 kilometers from the Ries Crater of southern Germany. It is strongly indicative that moldavites could not have derived from the Ries. This conclusion is consistent with

the chemical evidence that moldavites are not related to the Ries glass (Chao, 1963, p. 90).

This note is intended not only to record this evidence in favor of the cosmic origin of moldavites, but also to call to the attention of private collectors the need of searching for better preserved moldavites in order that more useful aerodynamic information regarding their place of origin can be obtained.

#### Acknowledgment

The author is grateful to Dr. Dean R. Chapman and Howard K. Larson of Ames Research Center, NASA, Moffett Field, California, for use of the casts of an australite indicator button and the large spalled teardrop illustrated in this short note. He is also indebted to Dr. Carleton Moore for the loan of australites obtained by Dr. H. H. Nininger from Hampton Hills, Kalgoorlie, Australia. He wishes particularly to thank Dr. Vladimír Bouška of Charles University, Prague, who planned and guided the author's field trips to the Bohemian and Moravian Basins, and to Mr. Jaromír Šofr of Třebíč for contributing the moldavite teardrop described.

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# SOME GEOLOGIC OCCURRENCES OF AUSTRALASIAN TEKTITES

by E. C. T. Chao

## Introduction

Many American investigators have visited the various tektite localities of Southeast Asia and Australia within the past few years (H. H. Nininger, W. Cassidy, E. P. Henderson, and V. E. Barnes). Except for the brief accounts by Barnes (1963), few have published geologic information concerning the occurrences of tektites. From late September to early December, 1962, the author visited several sites in the Philippines, the Dalat sites in South Viet Nam, sites on the Korat (Khorat) Plateau of Northeast Thailand, the Sangiran Dome site in Java and the Port Campbell and Stanhope Bay sites in Victoria, Australia. The Sangiran Dome, the Port Campbell and Stanhope Bay sites were visited in the company of Chapman and Larsen of the Ames Research Center. In addition to the field investigations, several museum collections and private collections of tektites were studied, and specimens were obtained for petrographic and chemical work to be reported elsewhere.

The purposes of these visits were several: (1) to obtain first-hand information on the geologic occurrences and stratigraphic ages of tektites and to determine, if possible, whether the geologic ages of all tektites of this vast strewnfield are consistent with the possibility that

all the tektites belong to the same event; (2) to investigate possible partially fused material that might be associated with tektites and that might be a clue to a possible terrestrial origin of tektites other than by meteorite impact; (3) to investigate the possible occurrence of meteorite craters which might be related to the present distribution of tektites; (4) to evaluate the evidence for estimating the number of tektites that fell in this strewnfield; (5) to collect tektites of known localities for detailed laboratory studies; (6) to inspect private tektite collections and collections from various museums and institutes with regard to their range of shapes, sculptures, physical properties, and glass or metallic inclusions. Many of these objectives were successfully or completely achieved. The results obtained on the geologic occurrences are reported here. Results of laboratory studies made on samples collected and obtained from this trip will be reported elsewhere.

Approximately 10 days were spent in the Philippines, 1 week in South Viet Nam, 3 weeks in Thailand, 1 week in Java and 3 days in Victoria. The report given here is therefore of a reconnaissance nature. Observations were primarily concerned with the stratigraphic sections in which tektite specimens occur. Emphasis was placed on determining the stratigraphic position of tektite-bearing beds and their geographic distribution, and on the collecting of datable material such as fossils and carbonaceous matter wherever possible. Interpretation of the local geologic history from these sections, particularly the evolution of the soil profile and

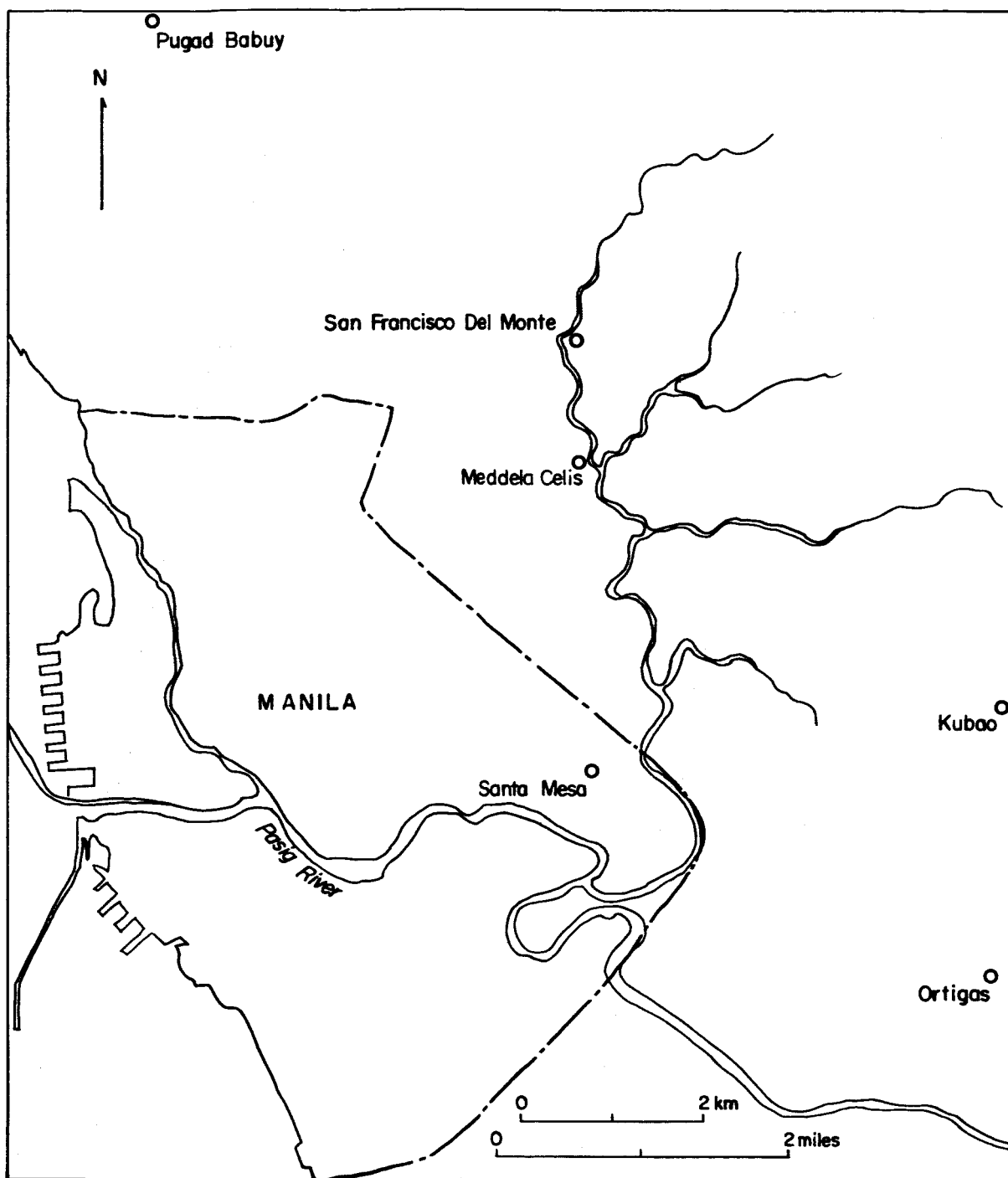


Figure 1. Index map of Manila region, Luzon, showing tektite sites.

subsequent processes of laterization, was a major and only partially successful task.

#### Sites near Manila and on Anda Island, Philippines

The Kubao, Santa Mesa, San Francisco del Monte, Meddella-Celis, Pugad Babuy and the new Ortigas sites were visited in the Manila area (fig. 1). Some of these sites were visited in the company of Dr. Otley Beyer. All were visited in the company of my colleague, Darwin Rossman. The general terrain and various sites near Manila were also viewed from the air at about 1000 feet. Two days were spent on Anda Island, but only parts of the island were covered.

The various tektite sites near Manila and elsewhere in the Philippine Islands have been described by Beyer (1961-1962) in his summary of more than 35 years' work on philippinites. Many of the sites, particularly those within the vicinity of Manila, have been greatly modified or destroyed by the construction of buildings. This is generally the case with the Kubao, the Santa Mesa and the San Francisco del Monte sites. There was little time during my visit either to collect tektites from these sites or to observe sections where the tektites are in place.

The San Francisco del Monte site.--This site, which had been highly disturbed by construction of homes and roads, was described by Beyer (1961-1962, p. 94-95, vol. 1) and Barnes (1963, p. 36). Barnes believed that

the tektites might have come from a tuff in the stratigraphic section of the area. If so, then the minimum age of philippinites should be Pliocene, the recognized age of the tuff. Outcrops of the tuff with remains of fossil wood can still be observed behind dwellings. Artificially flaked chips of tektites, together with chips of obsidian, were picked up along a path. The record is clear that no one has found tektites in situ in tuff, here or anywhere else in the Philippines. The site is definitely highly disturbed by human activities, both past and present, and it would be difficult to prove that tektites were embedded in tuff.

The Ortigas site.--The Ortigas site is a new site discovered in the spring of 1962 when construction work on a drainage ditch began on the Mandaluyong estate owned by Rafael Ortigas, Jr. The site is about 2 miles east of the city limits of Manila (fig. 1) on the east side of the intersection of highway 54 and Shaw Boulevard. It is an abandoned, terraced rice field situated on a gently sloping plain or terrace about 130 feet above sea level and 80 to 100 feet higher than the present alluvial valley. The underlying rocks are nearly flat-lying tuffaceous sandstone, conglomerate, and pyroclastic rocks of the Guadalupe formation of Pliocene age. The tuffaceous sediments are unconformably overlain by a blanket of tektite-bearing alluvial terrace gravel up to 6 feet thick.

A preliminary survey by Darwin Rossman in 1962 showed that the tektite-bearing gravel extends in a westerly to northwesterly direction, varying between 200 and 1000 feet in width. It is possible that the

tektite-bearing gravel is connected with the tektite-producing area of Santa Mesa and farther to the northwest with the Pugad Babuy tektite-producing area. This gravel deposit may represent an old river terrace, the site of an old river channel or the location of an old coast line. The last possibility is not entirely unlikely, as the gravels and tektites are extremely well rounded, like beach gravels.

The gravel deposit was exposed in the drainage ditch, as well as in a trench and a pit dug by the author to study the internal relationships of the gravel. It is typically rust colored and is generally less than 6 feet thick. The gravel consists of round pebbles and cobbles of andesitic rocks, tuffaceous sandstones, and silicified tuff, ranging from white to dark brown and purplish color and up to 5 inches in diameter. A few large, rounded cobbles of dark gray basalt are also present. Numerous manganese and iron oxide nodules averaging about 1/4 inch in diameter occur in the upper part of the gravel. Locally, these nodules are particularly abundant near the surface. The matrix of the gravel is gray to grayish white plastic clay. In some places, a layer of pebbly clay 5 or 6 inches thick occurs on top of the gravel, probably as the result of rice cultivation in the past. Stratification in the gravel is not easily seen because of the small thickness and poor exposures.

The precise age of the terrace gravel is unknown. Because of the high elevation of the terrace and the prolonged weathering required for the iron and manganese oxide nodular layers to form, it is probably Pleistocene in

age. It is almost certainly post-Pliocene, as it lies unconformably on a weathered surface of the Guadalupe formation of late Pliocene age.

Numerous shallow pits were dug by local residents and members of the ditch construction crew to recover tektites. During the author's visit, 184 tektites were recovered from approximately 1 cubic yard of gravel excavated in an undisturbed area at the site (figs. 2 and 3). The recovered tektites are mostly small and fragmental. Thirty-seven are rounded and pebble shaped. The largest is 1-1/2 inches in diameter (fig. 3). The surfaces of the well-rounded, pebble-shaped tektites are covered with crescent-shaped percussion marks. The large number of tektites here evidently has been the result of concentration by running water and does not reflect directly on the density of fall of the tektites.

The Meddela-Celis site.--At the Meddela-Celis site (fig. 1), along the east bank of a drainage canal, 3 rounded tektites were found embedded in a gravel deposit exposed along the stream. The gravel deposit, consisting mostly of light brown to white, subangular to rounded chert in a silty, sandy matrix is about 2 to 3 feet thick and occurs on both sides of a conduit through which the stream drains. The gravel lenses are younger than the underlying tuffaceous bed rock and are presently being actively reworked. The tektites were probably redeposited in the gravel lenses and are therefore somewhat older than the gravel.



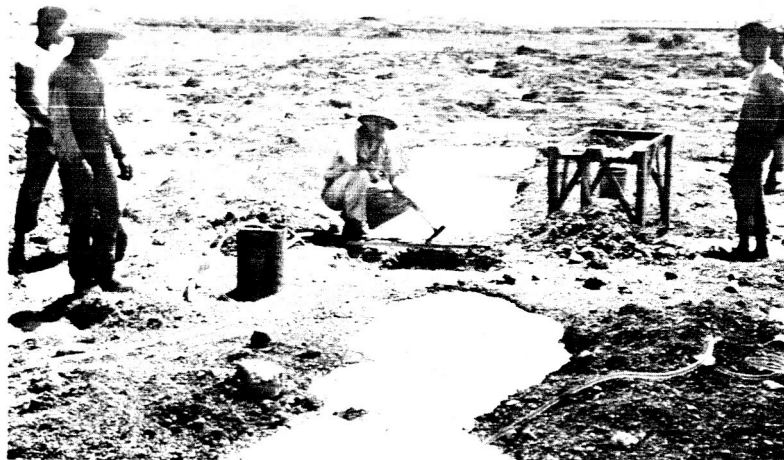


Figure 2. The Ortigas site, 5 miles east of Manila, in Mandaluyong, showing the terrace gravel from which abundant tektites were recovered. Yardstick indicates pit from which 184 tektites were obtained.

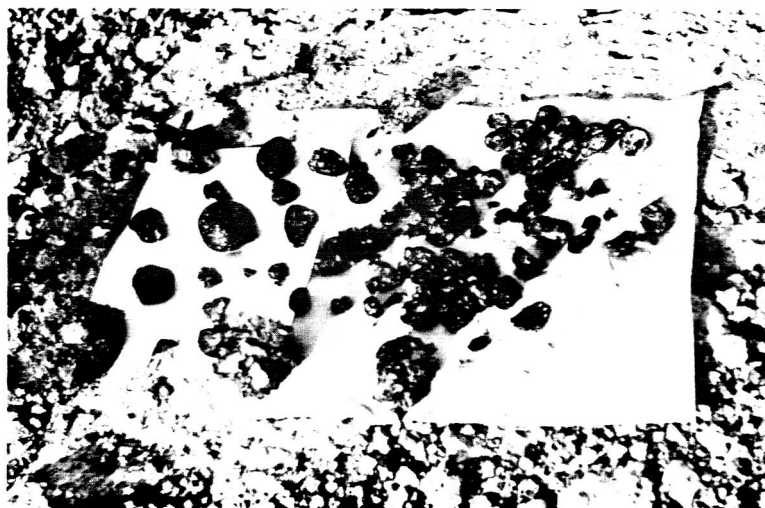


Figure 3. 184 tektites, mostly fragmental, some are well-rounded, recovered from dug pit shown in figure 2.

The Pugad Babuy site.--This site is north of Manila (fig. 1). The name means pig farm, and the outcrop visited is located on a pig farm owned by Mrs. Virginia West. The outcrop was exposed along a bank rising 10 to 12 feet above a rice paddy (fig. 4). The lower part of the outcrop consists of well-bedded massive gray tuff of the Guadalupe formation, 4 to 6 feet thick, succeeded by thin-bedded tuff, which is overlain in turn by about 4 feet of gray plastic clay. Above this is a layer 1 to 3 feet thick consisting of rusty colored gravel composed essentially of silicified tuff and chert with some iron oxide nodules. Above this gravel is a layer of pisolitic manganese and iron oxide nodules 1 foot thick. Three well-rounded tektites were found in situ in the gravel layer (fig. 5). The tektite-bearing section is nearly identical to that observed at the Ortigas site.

The Macandocandong and Auile sites of Anda Island.--Tektites have been reported and described as the Anda type from Cabarruyan Island (also known as Anda Island by the natives) of the northern Pangasinan province of Luzon about 150 miles northwest of Manila (Koenigswald, 1957, p. 372-373; Barnes, 1963). Koenigswald (1957) mentioned the finding of remains of *Stegodon* and of specialized *Elephas* of Upper Middle Pleistocene with the Anda type tektites. Barnes (1963), however, has pointed out that neither the tektites nor the fossils were found in situ.

Several villages--Macandocandong, Sablig, Auile, Namagbegan, Analateng, Berio, and Baranoy of San Jose and Anda on Anda Island--were visited in the company of Jose Santiago of the Philippine Bureau of Mines



Figure 4. Cross section at Pugad Babuy showing approximately 2 feet of terrace gravel overlying about 4 feet of gray clay above bedded tuff of the Pliocene Guadalupe formation. Hammer points to the location of a tektite which is in situ in the gravel.

and Eusibio de Castro of Anda. Mr. de Castro is most familiar with the tektite localities on this island and had acted as guide to previous investigators. Many fragmental tektites were found in chocolate-brown soil overlying limestone west of Sablig and near Macandocandong. Near Macandocandong, trenches were dug to recover tektites and to study the stratigraphic section. The best exposed section is located near Auile near the highest point on the island. Auile is approximately midway between Anda, 1.6 miles to the northwest, and Macandocandong, 1.5 miles to the southeast. Both Auile and Macandocandong are about a mile inland from the southwestern coast of the island.

Anda Island rises about 25 to 30 meters (80 to 100 feet) above sea level. At the base of the stratigraphic section there is a nearly flat-lying cross-bedded sandy siltstone. At Macandocandong, the sandy siltstone is overlain by a bed, up to six feet thick, composed of nodular or knobby limestone. The limestone is overlain, in turn, by several inches of chocolate-brown silty to clayey soil with scattered small manganese nodules. Thirty-seven tektites were collected on the surface of a plowed field here within an hour. Nearly twice this amount was recovered from several shallow trenches. One trench, 60 feet long, was dug in the plowed field down to the knobby limestone bed rock. One ant hill in this area also was excavated, as previous reports have mentioned tektite finds of Anda in ant hills (Beyer, 1961-1962). No tektites were uncovered in the ant hill. Several pits were dug into the underlying knobby limestone

in an attempt to find tektites in it, with negative results. All of the tektites recovered lie within the chocolate-brown soil layer. It was estimated that the tektite abundance is approximately one tektite per square meter. The lack of percussion marks on the Anda tektites suggest that these tektites have not been transported far by running water.

A better exposed section than that at Macandocandong was located about 1/2 mile east of Auile along the north side of the road (fig. 6). At the base of the exposed section is a nodular or knobby limestone, which here is only a few feet thick. This appears to be the same knobby limestone layer observed at Macandocandong. About 20 inches of brownish colored clay with abundant irregular whitish-gray limestone nodules and layers of large oyster shells overlies the grayish clay. The surface layer consists of about 20 inches of chocolate-brown silty clay containing pisolitic manganese and iron oxide nodules. The knobby limestone is overlain by grayish clay with large, scattered limestone concretions. According to Eusibio de Castro, tektites are found only in the chocolate-brown layer in the upper part of the section. The oyster shells were collected and identified as Middle Pleistocene in age by paleontologists of the Philippine Bureau of Mines (Darwin Rossman, oral communication).

The information obtained from Macandocandong and from Auile suggests that the Anda tektites are probably post-Middle Pleistocene in age. They occur on an erosional surface underlain by Middle Pleistocene calcareous sediments.

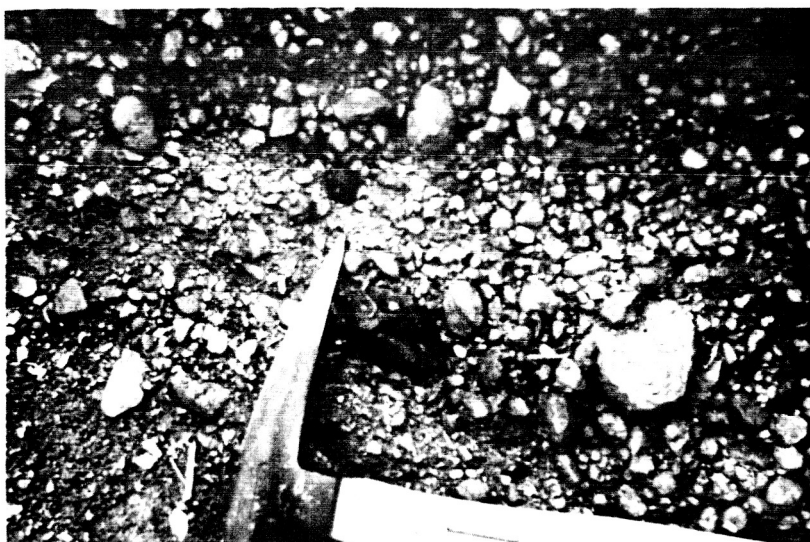


Figure 5. Photograph showing a round tektite occurring in situ in the gravel shown in figure 4 near the point of the hammer.



Figure 6. Geologic cross section 0.5 mile east of the Auile village on Anda Island, Pangasinan Province, P.I. Tektites of the Anda type were reported to occur in the chocolate-brown soil layer above the calcareous bed, which contains numerous Middle Pleistocene pelecypod fossils.

The similarity of the geological occurrences of all tektites in the Manila area and on Cabarruyan Island, described above, suggest that the philippinites are probably post-Middle Pleistocene age. Their absolute age is more difficult to determine. At the Ortigas site, the Pugad Babuy site and the Auile site the tektites occur below the pisolitic manganese and iron oxide layer. Many of the tektites recovered show abundant filling of iron oxide in vesicles and deep grooves. Contrary to Barnes' conclusion (1963, p. 38), the philippinites are definitely older than the major period of lateritization of these sites. It has been suggested that formation of manganese and iron oxide by lateritization requires perhaps as much as several thousand years (Sivarajasingham and others, 1962). If so, the minimum age of philippinites must be more than a few thousand years. The tektites in the Manila area occur in a terrace gravel which is now 80 to 100 feet above the present alluvial valley. The age of the terrace, or the period of uplift or change of sea level, is unknown.

#### The Dalat sites of South Viet Nam

The occurrences of Indochina tektites have been described by Lacroix (1935), Saurin (1935, 1944) and Saurin and Milliès-Lacroix (1961). The Dalat sites were visited by the author in the company of Prof. Edmond Saurin and Franz Rathman. Tektite localities visited are shown on figure 7.

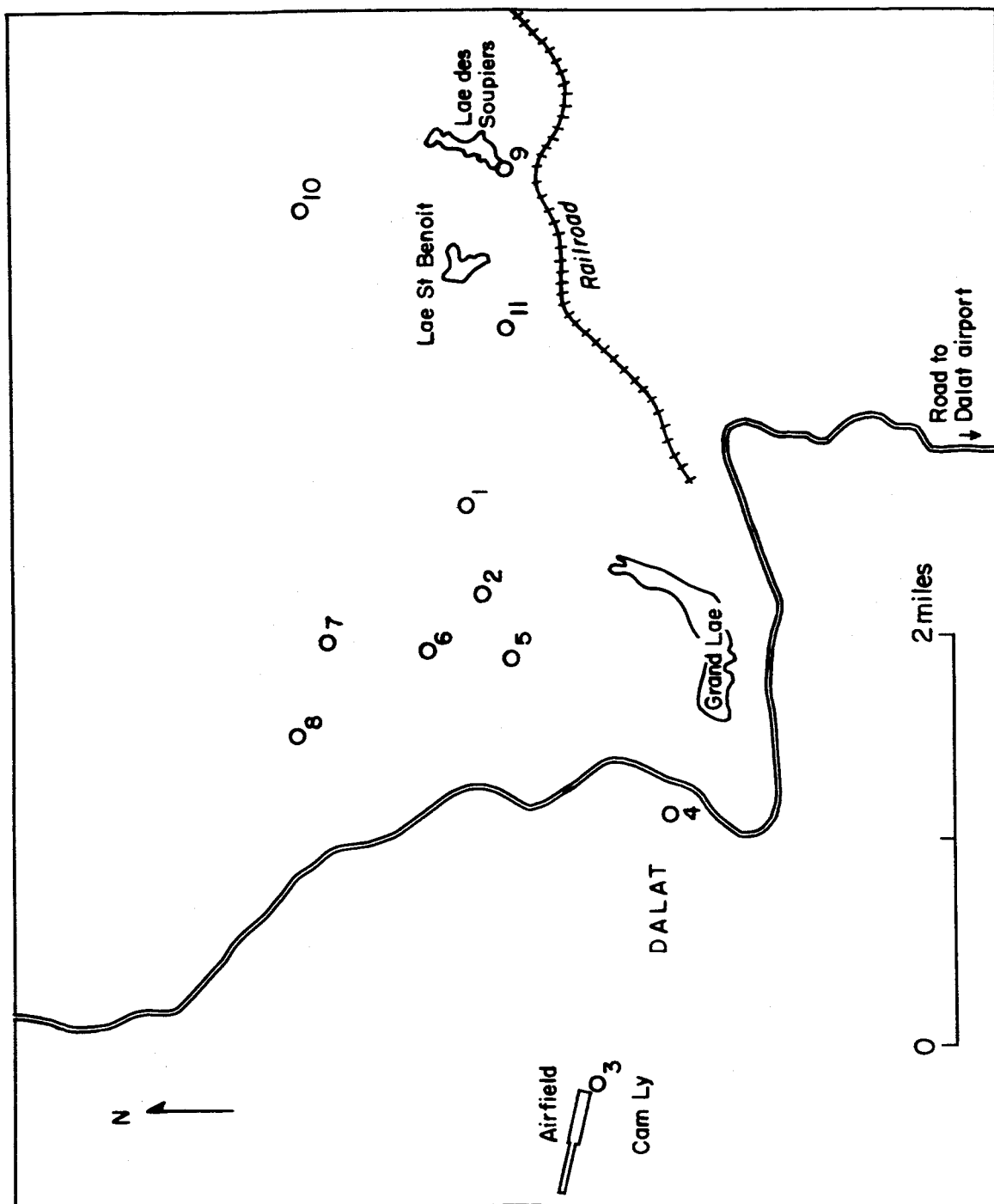


Figure 7. Index map of Dalat region, Viet Nam, showing tektite sites.



Dalat is underlain by Hercynian biotite granite to the southwest and west, and by mica schist of the Dalat series of presumed Cambrian to Silurian age to the east and northeast (Saurin, 1944). A small area of basalt a mile or so in its longest dimension occurs near the Cam Ly air-strip. This basalt unconformably overlies the biotite granite and is believed to be of Pleistocene age (Saurin, 1944).

Many tektite specimens were observed in situ in Dalat. One of the best exposures was in a 30-inch deep ditch at site 1 (figs. 1, 8, and 9). A soil layer at this locality, about 18 to 20 inches thick, consists of chocolate-brownish gray silt. It overlies a few inches to a foot of subrounded gravel. The gravel is succeeded downward by deeply weathered, yellowish-pink mica schist of the Dalat series. Near the top of the gravelly layer, fragments of carbonaceous matter up to an inch long occur in small lenses (fig. 8). The gravelly bed consists of subrounded pebbles of vein quartz, quartz-tourmaline rocks, and iron oxide nodules. The pebbles of vein quartz and quartz-tourmaline rocks, according to Professor Saurin, are derived from veins cross-cutting the mica schist. Several tektites were found in this gravelly layer, one of which is shown in figure 9 near the hammer head.

The carbonaceous matter collected from above the tektites was analyzed by the C-14 laboratory of the U.S. Geological Survey and was found to be  $1850 \pm 300$  years old. This is the minimum age of the indochinites. The gravelly bed may have formed an erosional surface on which the tektites



Figure 8. Geologic cross section exposed in a 30-inch deep ditch at the reactor site (IDC-1-62), Dalat, South Viet Nam. The top layer about 18 to 20 inches consists of chocolate-brownish gray silt overlying a gravel layer about 12 inches thick containing iron oxide nodules, and sub-rounded vein quartz, and tommaline quartz gravel. Yellowish-pink, weathered, micaceous soil of the Dalat Series underlies the stony layer. Hammer points to top surface of the gravel layer where fragments of carbonaceous matter were collected.



Figure 9. Photograph of the same ditch shown in figure 8 about 20 feet to the right of previous photograph. Hammer points to a tektite occurring in situ about 4 inches below the top surface of the gravel layer.

fell. How much older than the carbonaceous matter the tektites may be cannot be determined.

Various types of soil occur in the Dalat area in addition to that at site 1. A strikingly zoned soil was observed at sites 6 and 9 (fig. 7). At the south end of Ho Than Tho or Lac des Soupiers (site 9) 6 inches of chocolate-brown soil with organic matter (A zone) overlies about 12 inches of brownish-red to red silty clay (B zone). A discontinuous stony layer occurs near the base of the B zone where the soil grades into yellowish, mottled, micaceous silt composed of deeply weathered schist of the Dalat series (fig. 10). A small tektite was found in situ a few inches below the stony horizon.

A simpler soil profile was observed at site 7 (fig. 7) overlying deeply weathered saprolitic granite gneiss. An A zone of chocolate-brown only a few inches to a foot thick is present here. Tektites again were found in situ in the upper part of the saprolite (fig. 11).

Tektites were also found in soils on the Quaternary basalt at the eastern end of the Cam Ly airstrip (site 3, fig. 7). This indicates that the tektites of the Dalat area are younger than the Quaternary(?) basalt.

Nearly 2000 tektites were collected at Dalat. Sites 1 and 11, the San Van Dong site (St. Benoit), yielded the most specimens. Both sites were being bulldozed at the time of the visit. Most specimens are fragmental and had been broken for some time, as shown by etching of the broken surfaces. Many



Figure 10. Geologic cross section along a road cut at the south end of Ho Than Tho (lake) (IDC-9-62), near Dalat showing about 6 inches of chocolate-brown soil (A Zone) overlying 12 inches of brownish-red silty clay (B Zone) with a gravel layer occurring near the base. The brownish-red silty clay grades downward into the yellowish and pink mottled micaceous silty clay (C Zone of the soil profile) of the weathered schist of the Dalat Series. Hammer points to an indochinite occurring in situ about 6 inches below the gravel layer.



**Figure 11.** Geologic cross section along a road cut 0.7 mile WNW of the reactor site, Dalat, showing the saprolite of deeply weathered granite gneiss of the Dalat Series underlying 6 inches to a foot of chocolate-brown soil. Hammer points to a tektite (black) occurring in the saprolite or C Zone of the soil profile.

specimens are of tear-drop, rod or dumbbell shape. Lack of crescent-shaped percussion marks indicates that they have not been transported by running water for any appreciable distance. A rough maximum estimate of the local abundance of tektites based on the number of specimens collected at site 1 is 1 tektite per square foot. As the majority of the specimens are fragments, the number of tektites should perhaps be reduced by a factor of 3. The areal density is certainly higher than that of the Macandocandong site of Anda, in the Philippines.

Saurin (1944) has observed that indochinites occur on a gravel terrace 50 meters above the bed of the Song-Ba river, 4.3 miles east of Boun-Thanh on the M'Drack Plateau of eastern Cambodia. He also found tektites in siliceous gravel on a small plain of old alluvium 1.2 miles southeast of Boun-Dlo, at the northern border of the South Annam Massif. According to Saurin, the indochinites are associated with early Quaternary alluvium or with red soil on basalt which may be of the same age. The geologic age of indochinites, on the basis of observation in the Dalat area, cannot be younger than about 2000 years or older than the Quarternary(?) basalt. This range of possible age overlaps that for the philippinites.

#### Sites on the Korat Plateau, Northeast Thailand

The author visited the Korat Plateau for two weeks in the company of Mr. Amorn and a mechanic and driver of the Thai Royal Department of

Mines. Barnes (1961, 1963; Barnes and Pitakpaivan, 1962) had previously visited various parts of the Korat Plateau and briefly described the sites near Phang Doeng and Non Sapong. Tektites are so widespread in this part of Thailand that, excluding the areas of rice paddies and dense vegetation, they can generally be found as float everywhere, particularly in areas where laterites are well developed. The underlying rocks are a series of non-marine red beds that include sandstone, conglomeratic sandstone, conglomerate, and shale of the Korat (Khorat) series assigned to the Triassic and in part to the Jurassic (LaMoreaux and others, 1959). The Korat series comprises three formations according to LaMoreaux and others. From base to top these are the Phu Kadung formation, 400 to 480 meters thick, composed of variegated shale and interbedded arkosic sandstone; the Phra Wihan formation, 450 to 500 meters thick, composed of gray, green and tan, cross-bedded sandstone; and the Phu Phan formation, about 300 meters thick, composed of white to tan conglomeratic sandstone. Poorly cemented to medium-well cemented concretionary laterite and hard-crust laterite overlie the bedrock in discontinuous but widespread occurrences.

Most of the known tektite localities of Thailand (fig. 12) are based on information supplied by the Royal Department of Mines, and some have been described by Barnes (1963). Localities where tektites have been collected during the author's trip are shown by separate symbol. Where samples were found in situ, a solid symbol is used. The locations shown are not intended to indicate new discoveries, as tektites are so widespread



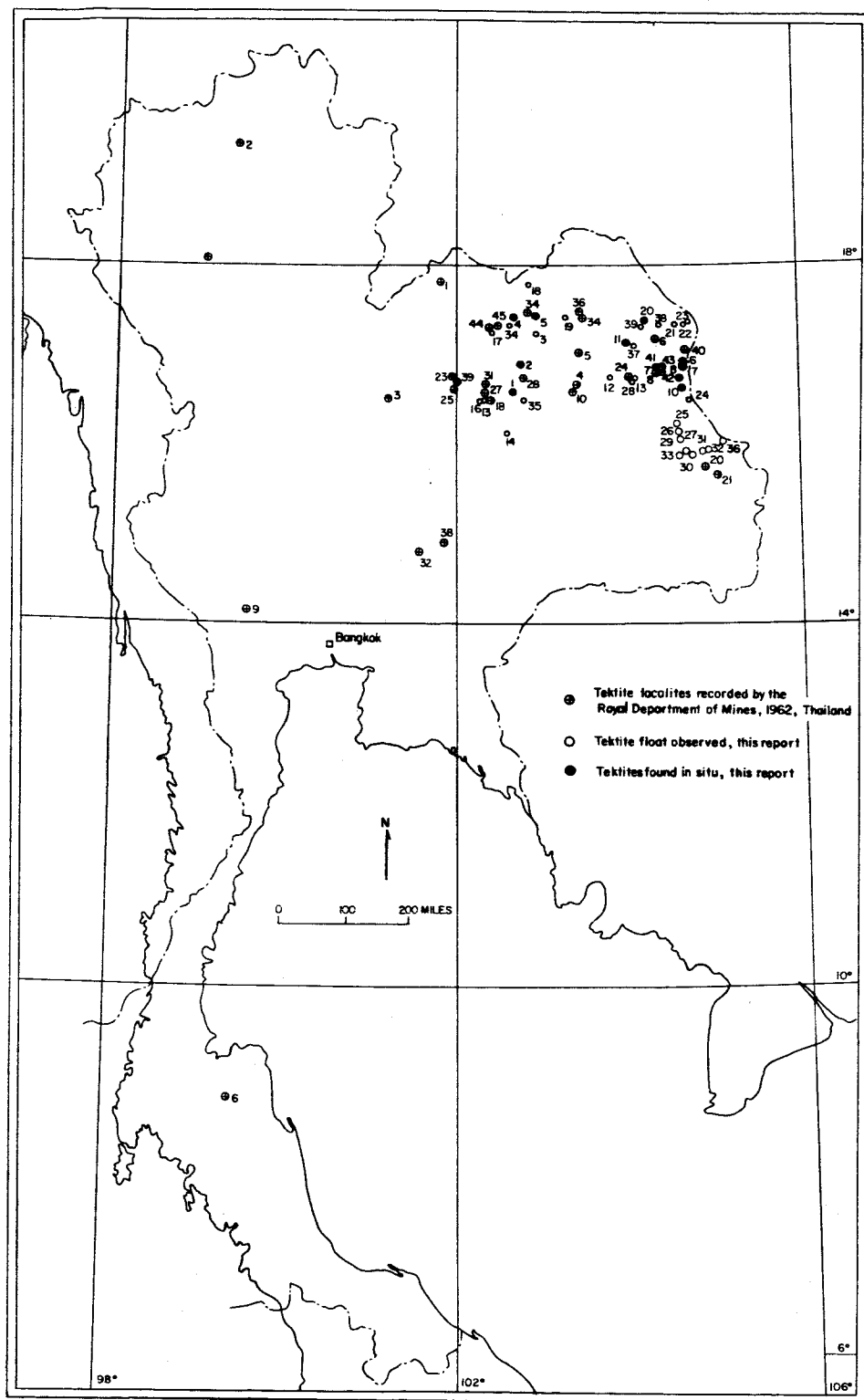


Figure 12. Map of Thailand showing known tektite localities.



that part of the map would be filled with symbols. Another thirty or so localities could probably be added in another week's work just by traveling different roads. The symbols are shown merely for convenience of reference for locations of samples and for the stratigraphic sections to be described.

Locality 1, the Mo Din Dang sand and gravel pit in which a curved tektite was found in situ, is located on an upland surface at an elevation of about 175 meters above sea level, 2.8 miles north of Khon Kaen. The pit is about 500 feet west of the highway between Khon Kaen and Udon. It is excavated in purplish-red to red, flat-lying, well stratified sand and gravel of possible Quaternary age which overlies yellowish pale brown sandstone in the upper part of the Korat series. The sandstone is not exposed in the pit. Red, medium to coarse sand about 5 to 10 feet thick occurs at the bottom of the pit. This sand is overlain by 10 to 15 feet of gravel. The gravel consists of pebbles, 1/4 to 2-1/2 inches in diameter, composed predominantly of quartz, and whitish-gray chert and subordinately of black and red chert, in a red sand matrix. The gravel is overlain by 1 to 3 feet of loose sandy soil with very sparse pebbles. A layer of well-cemented laterite consisting essentially of clayey silt and iron oxide occurs in the lower part of the sandy soil directly above the gravel. Small angular fragments of milky quartz also occur in the soil. The curved tektite was found in the hard laterite, where it is exposed in the east wall of the pit (figs. 13 and 14). The tektite is



Figure 13. Photograph showing a portion of the east wall of the Mo Din Dang gravel pit located 2.8 miles north of Khon Kaen (TC-1-62), Thailand. Hammer marks the boundary between the loose surficial sandy soil and 1 foot of hard crust laterite which protrudes slightly from the wall. The laterite overlies 10 to 15 feet of stratified Pleistocene (?). Hammer points to a curved thialandite occurring in situ in the hard crust laterite.



Figure 14. Close-up view of a curved thialandite occurring in situ in hard crust laterite (4 inches from the point of the hammer) in the east wall of the Mo Din Dang gravel pit shown in figure 13.

evidently younger than the Quaternary(?) gravel and older than the laterite.

Possibly the youngest formation on which tektites were found in Thailand is the Mukdahan gravel at Ban Nong Aek (locality 10; fig. 12). A section of this gravel several feet thick is exposed in a pit on the east side of the highway between Mukdahan and Nakhon Phanom. The locality is about 150 meters above sea level and about 20 meters or 65 feet above the Mekong River. The gravel consists largely of well-rounded milky quartz pebbles, 1/2 to 2 inches in diameter, and also some gneiss and quartzite pebbles. Concretionary laterite 10 to 30 inches thick overlies the quartz gravel. About 20 inches of grayish-white sand with a few iron oxide nodules and subangular quartz pebbles, in turn, overlies the laterite. One platy tektite was found embedded in the upper part of the concretionary laterite layer. The quartz gravel is believed to have been derived by weathering from conglomerates of the Korat series. The age of the gravel is believed to be Quaternary. As the Quaternary geologic history of the Korat Plateau has yet to be studied, it is not possible to demonstrate the relative ages of the Mukdahan quartz gravel and that found at Mo Din Dang.

Many thailandites are found in situ in lateritic soils widely developed in areas underlain by sandstone and shale of the Korat series. The lateritic soils are found both in areas of the flat upland surface, as the localities near Ban Nong Kong (locality 2), Ban Pak Dong (locality 4), Ban Phon Thong (locality 5), Ban Tong (locality 6), Ban Pong

(localities 7 and 8), Ban Nong Suai Lai (locality 9), and Ban Kusuman (locality 20), and on hills rising above the upland surface as locality 11, about 10.5 miles southwest of Sakon Nakhon.

A well-exposed lateritic soil can be seen in a roadside pit about 1 mile north of Ban Nong Kong (locality 2, fig. 15). The top zone of the soil is about 14 inches thick and is composed of yellow, silty sand with scattered, small, iron oxide nodules. Tree roots extend down to the bottom of this zone. It is underlain by 30 to 40 inches of medium-well cemented concretionary laterite. No pebbles are present in the laterite. Highly irregular or concretionary fragments of the sandstone bedrock of the Korat series underlie the concretionary laterite. A tektite about 2 inches long was embedded in the concretionary laterite (fig. 16) 14 inches below the upper contact of the laterite layer. Because the tektite is the only coarse fragment in this layer, it is believed that its position represents approximately its site of fall without much transportation by running water. The fall of this tektite clearly predates the period of lateritization. At this locality the areal density of the tektites is probably 1 per many square meters.

Another tektite was observed in situ in a ditch (fig. 17) about 0.6 mile north of Ban Kusuman (locality 20). Here pea-sized nodules in the lateritic layer occur in a clayey matrix that extends almost to the surface. This lateritic layer is about 40 inches thick, is brown, and rests



Figure 15. Cross section showing a typical occurrence of medium-well cemented concretionary laterite developed in silty sand overlying the medium-grained Triassic Phu Phan sandstone. The concretionary laterite layer is about 3 feet thick and overlies irregular fragments of sandstone. It is sharply separated from the overlying 14 inches of thick silty sand. Location TC-2-62, about 1.2 miles north of Ban Nong Kong, north of Khon Kaen.





Figure 13. Photograph showing a portion of the east wall of the Mo Din Dang gravel pit located 2.8 miles north of Khon Kaen (TC-1-62), Thailand. Hammer marks the boundary between the loose surficial sandy soil and 1 foot of hard crust laterite which protrudes slightly from the wall. The laterite overlies 10 to 15 feet of stratified Pleistocene (?). Hammer points to a curved thialandite occurring in situ in the hard crust laterite.



Figure 16. Cross section 15 feet to the right of locality of figure 15, showing a tektite in situ in the concretionary laterite layer (tektite is near the point of the hammer). The tektite is the coarsest fragment in the section. The concretions consist of sand cemented by iron oxide. TC-2-62.





Figure 17. Cross section of the west bank of a ditch 0.6 mile north of Kusuman, Thailand (TC-20-62), showing the occurrence of a small, disc-shaped tektite within the concretionary lateritic zone of the profile (tektite is near the point of the hammer). The lateritic zone is about 40 inches thick.

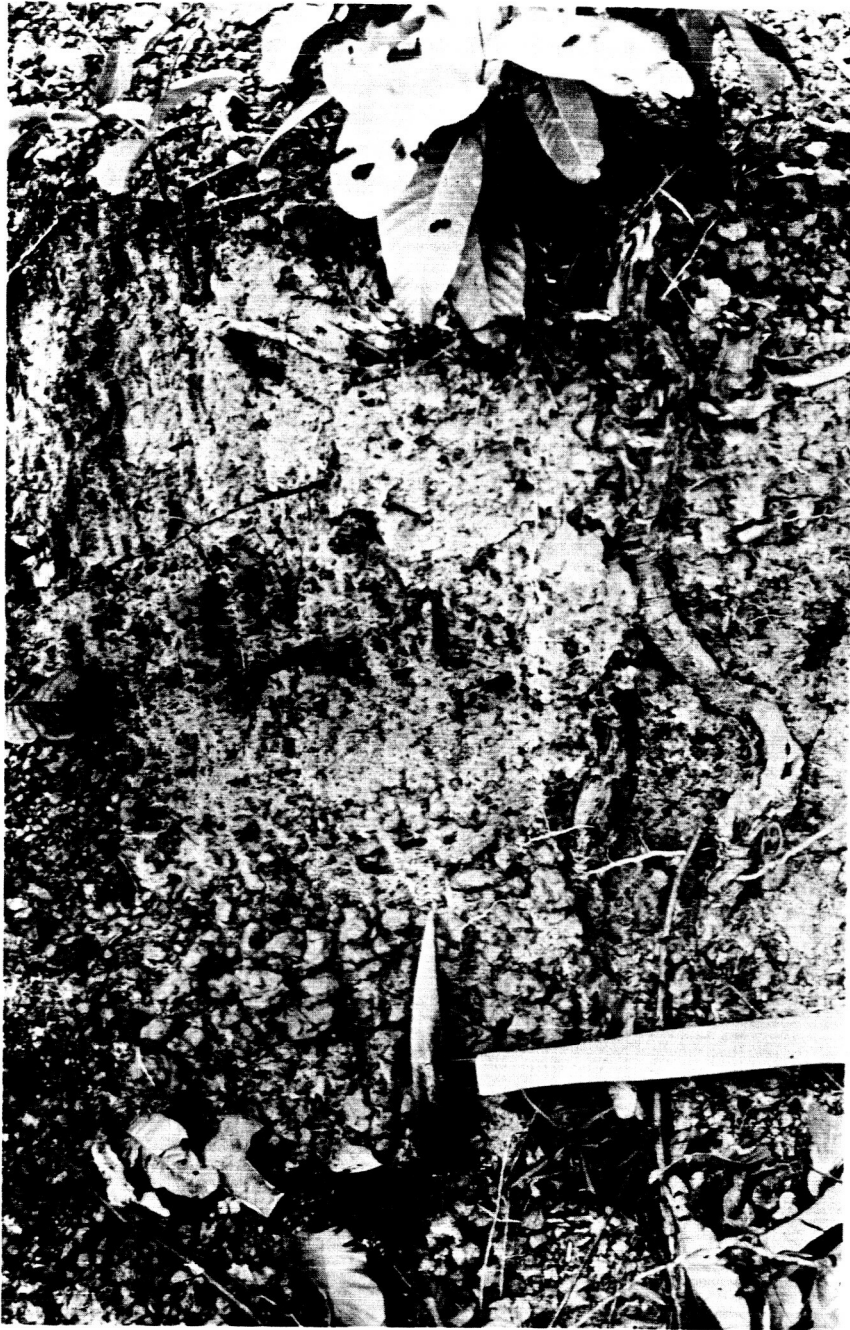
on gray, plastic clay derived from weathered shale of the underlying Korat series.

Similar soil profiles in which tektites were observed in situ are exposed near Ban Tong (locality 7, fig. 18) and near Ban Nong Suai Lai (locality 8, figs 19 and 20). At both of these localities, concretionary laterite occurs about 20 inches below the surface, beneath a sandy upper soil zone. Six tektites were found in situ in the Ban Nong Suai Lai area alone. They were in the upper part of the laterite a few inches below the top of the lateritic layer.

Massive or lumpy thailandites known as the Muong Nong type were also collected from several localities, one of which is in the central part of a structural dome north of Kuchinarai at Ban Na Khu (locality 13). There they were found embedded in white sand formed by weathering of underlying sandstone of the Korat series. Laterites do not occur on the Korat series in this area.

The geologic occurrences of thailandites described above are similar to those at Nong Sapong (locality 40) and Phang Daeng (Ban Pung Dang locality 41) briefly mentioned by Barnes, except that the sizes of the tektites from these latter localities are much larger.

The tektites observed in the lateritic soils are older than the enclosing laterite. Once emplaced they lay buried in a mechanically undisturbed soil. Both the gravel of Mo Din Dang, which overlies sandstone, and the Mukdahan quartz gravel of Ban Nong Aek, which overlies conglomeratic sandstone, are unrelated in gross chemical composition with the tektites



**Figure 18.** Cross section of the bank of a shallow laterite pit located about 1.2 miles south of Ban Tong, Thailand. A platy tektite occurs in situ, a few inches below the top of the concretary laterite (2 inches above the point of the hammer). The overlying sandy soil is about 20 inches thick.



Figure 19. Cross section of bank of a shallow laterite pit near Ban Nong Suai Lai, Thailand. Tektite near point of hammer occurs in situ about 3 inches below the top of the concretionary laterite layer. The overlying sandy soil is 28 inches thick.

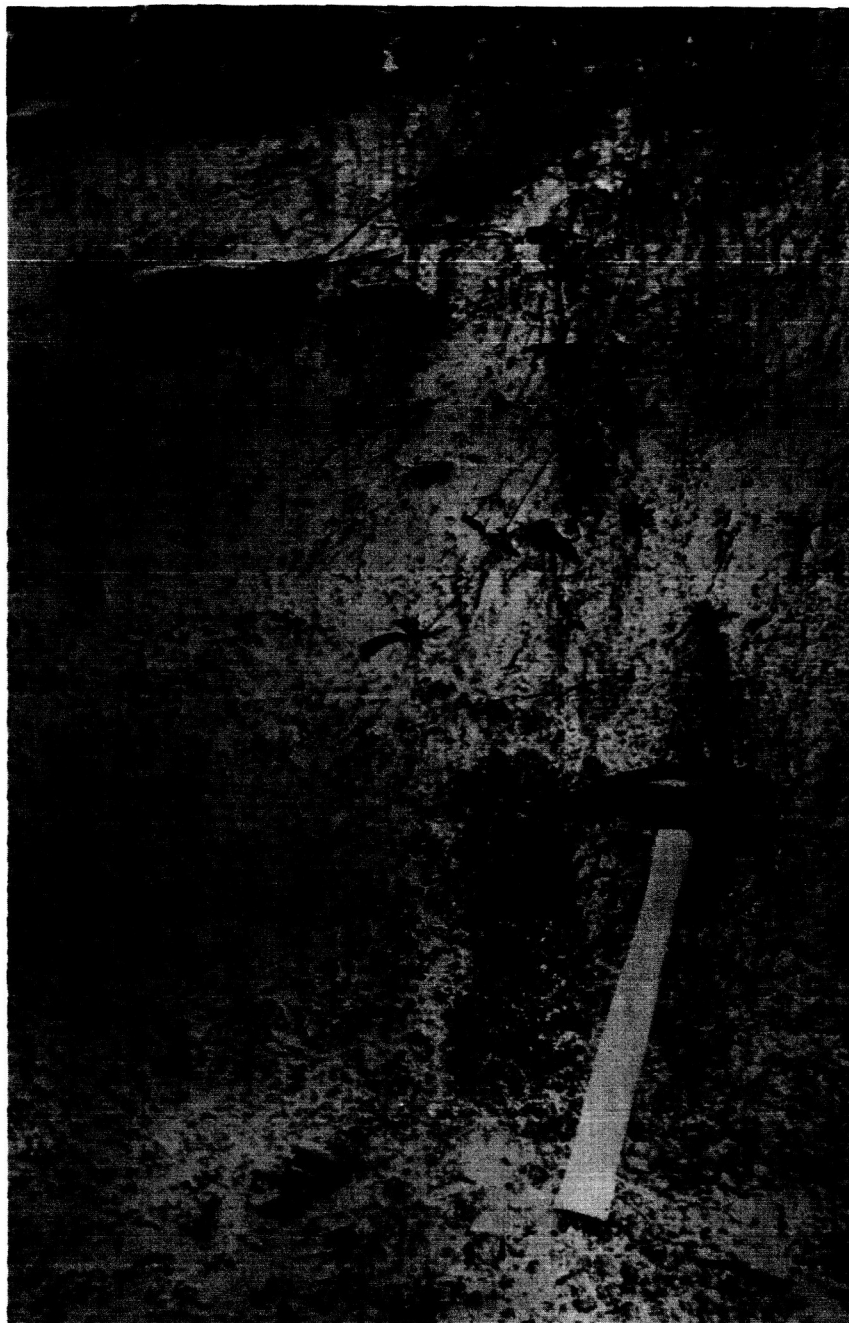


Figure 20. Cross section of bank of a shallow laterite pit near Ban Nong Suai Lai, Thailand. A platy tektite about 1.5 inches to the left of the point of the hammer occurs in situ about 6 inches below the top of the concretionary laterite layer.

found in the laterites immediately overlying these gravels. It does not appear, therefore, that the tektites could have been formed in place by any kind of melting mechanism, nor could the larger tektites, which appeared to Barnes (1961) to have been formed "in a puddle," be formed in place. There is no evidence that the thailandites were derived from pre-laterite soils overlying the sandstones of the Korat Plateau as suggested by Barnes and Pitakpaivan (1962).

In all of the Thailand occurrences, the tektites represent the coarsest fragments in the material in which they were embedded. They could not all have weathered out of the underlying bedrock because they are found in soils developed on Quaternary(?) gravels in some cases and on various sandstone and shale units in the Korat series in other cases. Thailand tektites are younger than the Mukdahan gravel. The age of the thailandites, on the basis of the general geologic evidence, appears to be similar to that of the philippinites and the indochinites.

#### The Sangiran Dome sites of Java

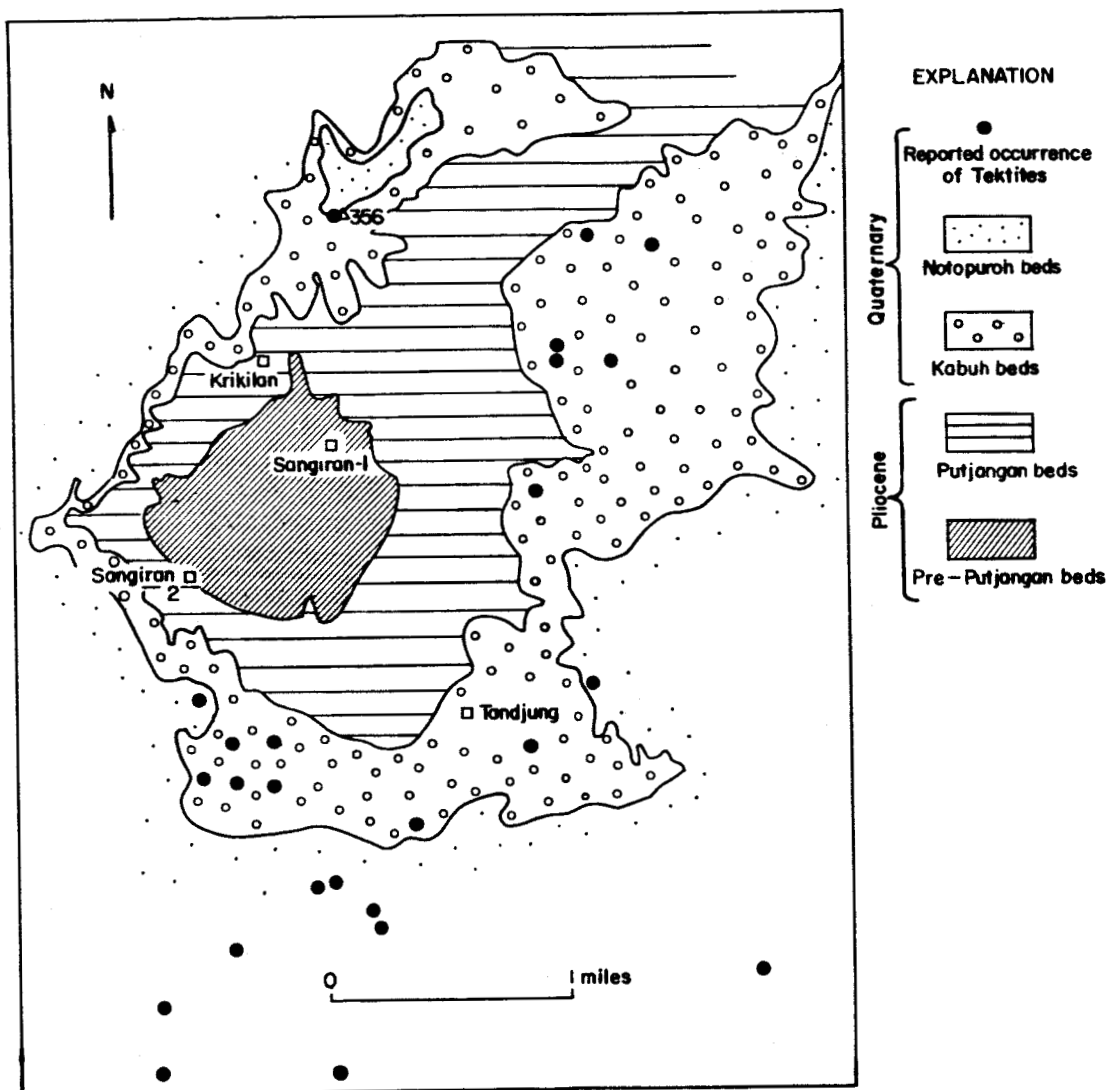
In Java there was time to visit only the sites at the Sangiran Dome area, about 7 miles north of Solo or Surakarta. Mr. Soeradi of Djawatan Geologi (Geological Survey of Indonesia) accompanied the author during the three days spent in this area. Professor George H. Hansen, who was teaching at the Gadjah Mada University of Djokjakarta, also spent a few hours with the author at the site. Dean R. Chapman and Howard K. Larsen

of Ames Research Center, NASA, also spent part of a day there during this visit.

The geology of the Sangiran Dome area has been studied by several authors (Es, 1931; Marks, 1953) because of the abundant *Pithecanthropus* remains found in this area. Von Koenigswald has collected tektites in this area and described their geologic occurrence (1960), and the area also was visited and described by Barnes (1963). The Sangiran Dome is a breached structural dome, the center of which is a topographic depression. The Kabuh beds of Middle Pleistocene age form a cuesta that encircles the structure. The central depression is underlain by fossiliferous sediments of Pliocene age.

Barnes (1963) published a map showing the tektite localities of the Sangiran Dome area and indicated that the sites were mapped by Professor George H. Hansen. During our visit, a similar map showing the tektite localities was given to the author by Mr. Roseman, a long-time friend and collecting guide of Professor von Koenigswald. This map is shown in figure 21. The generalized geology shown is based on work of Marks (1953). The reliability of this map is open to question because, according to Mr. Roseman, he plotted the locations of the tektite finds according to oral descriptions of the locations from the natives who actually found the tektites. Mr. Roseman himself is familiar with only two of the localities shown.

Von Koenigswald (1960) indicated that at least 10,000 tektites,

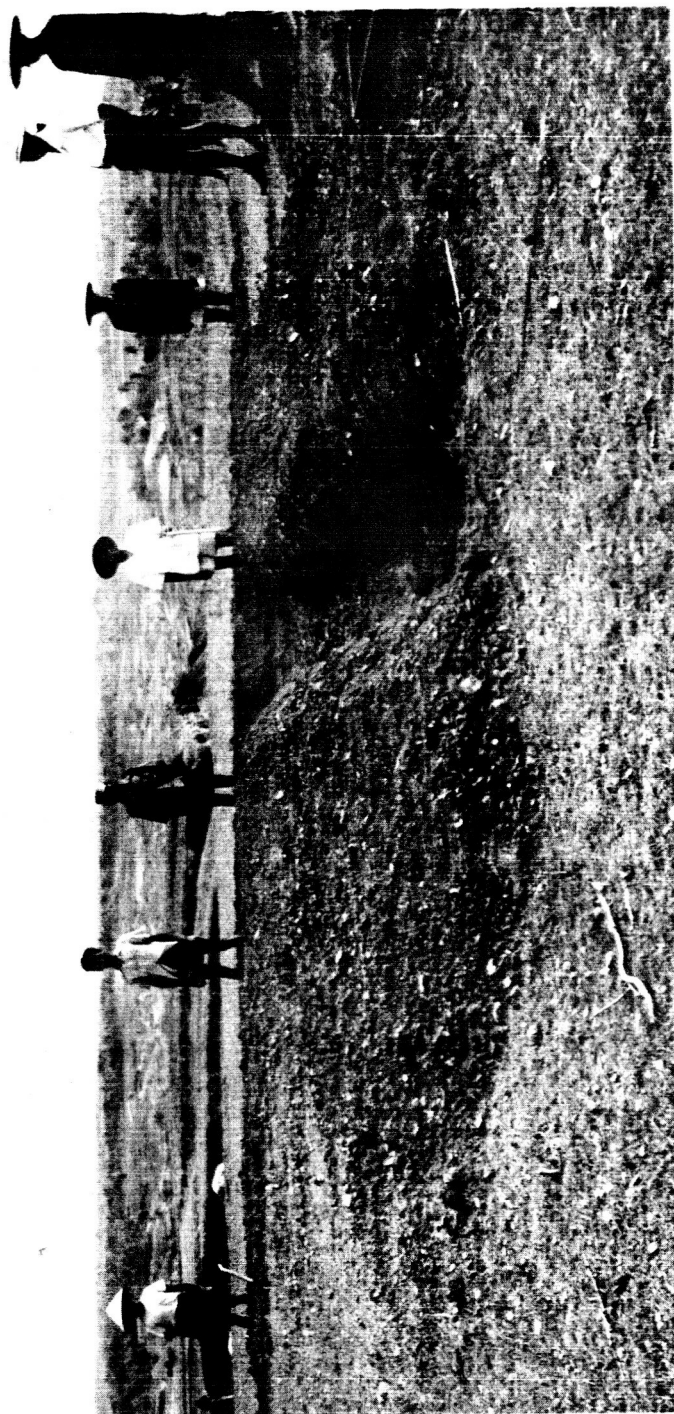


**Figure 21. Geologic sketch map of Sangiran Dome, Java, showing known tektite localities.**



mostly fragments, had been collected from Sangiran. The best site for collecting is on the northern rim of the structure at triangulation station 356, about 1 mile north of the village Krikilan. The stratigraphic section consists of dark gray shale of the Putjangan beds of Pliocene age overlain by about 4 feet of nodular limestone, in turn overlain by about 80 feet of cross-bedded conglomeratic tuffaceous sandstone of the Kabuh beds (fig. 22). Pebbles in the Kabuh beds are predominantly andesite and weather easily into crumbly material. Vertebrate fossils are found near the basal part of the sandstone. The upper part of the section consists of 2 to 5 feet of lag gravel. It is an unstratified deposit consisting predominantly of gray chert pebbles, which in the upper part of this gravel are deeply weathered. The gravel clearly accumulated as a result of prolonged weathering of the underlying cross-bedded conglomeratic tuffaceous sandstone.

According to Mr. Roseman and Professor von Koenigswald (oral communications, 1963) tektites were collected only on the surface of the flat top of a ridge at Station 356 and were never found embedded in the Kabuh beds. In an attempt to verify this, the author made two trenches forming a T-shaped pattern, one parallel to the ridge about 30 feet long, and the other 20 feet long (fig. 23). Both trenches were about 3 feet wide and 2 feet deep. Deeply weathered chert gravel was encountered 2 to 3 inches below the surface. The excavated gravel was sieved in an attempt to recover tektites. None were found, although nearly 400 javanites were



**Figure 22.** Geologic cross section showing the thin layer of unstratified lag gravel overlying the Middle Pleistocene Kabuh beds.



Figure 23. Photograph showing the gently dipping surface of the northwestern rim of the Sangiran Dome at triangulation station no. 356, 6 miles north of Surakarta, Java. The surface was underlain by an unstratified lag gravel as shown by the T-shaped trench. Some 300 javanites were reportedly found on top of this surface. None were found within the lag gravel.

reported to have been found at this site. The javanites here apparently do not accumulate by weathering out of the underlying Kabuh beds.

Probably the javanites did not fall until after the Kabuh beds had been deposited and undergone a lengthy period of erosion while the lag gravel was being accumulated. The lag gravel on which the javanites are found may post-date the folding that formed the Sangiran Dome, and the surface underlain by the gravel may represent an erosional surface upon which the tektites fell. The exact age of this lag gravel is unknown. The occurrence of tektites in the southern part of the area underlain by the Notopuroh beds indicates that the javanites are younger than the Kabuh beds, which are assigned to the Middle Pleistocene by von Koenigswald (1960).

#### The Port Campbell and Stanhope Bay sites of Victoria, Australia

A field trip to the Port Campbell and Stanhope Bay sites of Victoria was arranged by George Baker and Edmund D. Gill in December 1962. Other participants included Dean R. Chapman and Howard K. Larson.

The geologic occurrences of tektites at these sites have been described in some detail by George Baker (1962), who concluded that the australites are probably not less than 3000 or more than 6000 years old. A detailed restudy of the geologic age of australites in the Port Campbell area by Baker, E. D. Gill and the author is now underway. The short description given below outlines the problem of the determination of the

geologic age of australites.

The coast of Victoria near Port Campbell is a vertical sea cliff 150 to 250 feet high. Most of the cliff face is cut in flat-lying Miocene limestone. Near the top of the cliff is an irregular bed of variegated clay and sandy clay up to 10 to 20 feet thick, believed to have been formed by the weathering and leaching of the underlying Miocene limestone. A thin layer of iron oxide nodules called buckshot gravel overlies this clay. Locally, a complex soil up 10 feet thick with alternating light and dark bands overlies the buckshot gravel (fig. 24). Tektites are reported to occur in a sandy layer of the soil slightly above the buckshot gravel. The buckshot gravel is interpreted by E. D. Gill (1953) as a product of deflation or wind erosion, and the time of deflation was probably the post-glacial thermal maximum (Gill, 1955a, 1955b, and 1956).

At Stanhope Bay a distinctive aeolian deposit of Pleistocene age (Gill, oral communication, 1964) occurs above the mottled clays, and the buckshot gravel here overlies the aeolian deposit (fig. 25). Tektites were found as float above the aeolian deposit. Just how much of the Pleistocene period is represented by this deposit is not known. The tektites at this site are probably younger than the aeolian deposit. It is hoped that the joint study of the Port Campbell occurrences can help clarify the geologic age of the australites.



Figure 24. Cross section west side of gravel pit, east of Port Campbell, Victoria, Australia, showing a 10-foot thick sequence of soil profile overlying weathered Pliocene(?) clay. The boundary was marked by a thin buckshot layer (arrow). Miocene limestone that underlies the Pliocene(?) clay is shown in the foreground.



Figure 25. Cross section of a sea cliff near Stanhope Bay, Victoria, Australia, showing the Pleistocene aeolianite (marked by steeply dipping cross-bedding) overlying Pliocene(?) clay and Miocene limestone (white, lower part of the cliff). Standing from left to right, Dean R. Chapman, George Baker, Edmund D. Gill, and Howard K. Larson.

Comparison of the geologic age with  
K/Ar age of Australasian tektites

An unambiguous geologic age for tektites can be determined only if a fresh, unworn tektite specimen is found in situ in a geologic formation that can be accurately dated either by fossils or materials datable by absolute geochronologic methods. No occurrence described in this paper fulfills this condition. The philippinites, where found in situ, cannot be precisely dated because the tektites have been transported and redeposited by running water; the gravel deposit in which they were embedded as yet cannot be closely dated. Indochinites from Dalat are older than 2000 years and younger than the basalt, but the basalt has not been closely dated. The Thailand tektites are younger than the gravel deposits they overlie, but the age of the gravel is not known. Javanites from the Sangiran Dome are definitely younger than the Kabuh beds of Middle Pleistocene age, but the minimum age is not known. The australites from the Port Campbell and Stanhope Bay area of Victoria are probably younger than the aeolian deposit of Pleistocene age, but precise age of this deposit is not known. At present there is no evidence to indicate whether the Australasian tektites are of the same age or of different ages. They are probably of Pleistocene age or younger, but they could all be as young as 5000 years, as suggested for australites by Baker, or as old as 100,000 or 500,000 years or possibly older.

The K/Ar ages of the Australasian tektites determined by Gentner and Zähringer (1959), and Zähringer (1963) have been revised to about 700,000 years. The K/Ar ages are all much greater than the 5000 years suggested by Baker for australites and greater than the probable maximum geologic ages of the tektites at certain sites. Baker suggested that the time of formation of the tektite glass (K/Ar age) and the time of fall (geologic age) may not have to be the same. This is not likely if the tektites were formed either by terrestrial or lunar meteorite impact as indicated by the metallic spherules found in tektites (Chao and others, 1964). Long times in space appear to be ruled out by the absence of aluminum 26 that would be produced by cosmic ray bombardment in space (Viste and Anders, 1962).

Several possible explanations may account for apparent discrepancies between K/Ar age and geologic ages of the Australasian tektites: (1) The geologic time scale has not been firmly fixed for the past half a million years. Radiocarbon dating is not applicable to ages greater than 50,000 years, and the precision of the K/Ar method of age determination needs to be improved in order to yield meaningful ages of less than a million years. Only a very small amount of argon gas is measured by the K/Ar method in Australasian tektites, and the probable error is large enough to account for the apparent discrepancy of the K/Ar ages and the still less precise geologic ages. (2) It is possible that during the formation of the tektite glass, Ar<sup>40</sup> was not completely driven off. This



is suggested by laboratory experience in the outgassing of tektite glasses. If this is the case, the K/Ar ages are greater than the true ages of the tektites. (3) Perhaps the weakest link in solving the geologic ages of the tektites is the difficult problem of determining the relation of the tektites to the deposits in which they occur. There is the possibility that the tektites have been reworked and redeposited, and the age of the deposit thus gives only a minimum age of the enclosed tektites.

From the standpoint of origin, one of the most important questions is whether all the Australasian tektites are the same age or different ages. A much more complicated sequence of events would be required to account for differences in age. The available data in the Australasian tektite ages is consistent with the hypothesis that they were formed by a single event and were deposited in a single fall.

#### The problems of estimating the density of fall of tektites

Assuming an impact origin for tektites, the geographic distribution and the number of tektites recovered from various localities have direct bearing on questions concerning the amount of glass produced by the impact event and how the ejecta were distributed. This, in turn, bears on the problem of the terrestrial or lunar origin of tektites. Many difficulties are involved in making an estimate of fall density: (1) In many areas the original distribution and density of fall have been modified by

subsequent transportation and redistribution by running water. (2) Although tektites have been known for decades, a detailed study aimed at determining their actual distribution has not been made. All the information available is incomplete, including observations reported in this paper. (3) From the available data it appears that there are clusters of tektites that fell in various parts of the strewnfield. The sampling of a small area as representative of the strewnfield as a whole will therefore tend to be highly misleading. (4) Much of the material, such as that collected from the Dalat area is fragmental, so that correction must be made for the increase in number of specimens due to fragmentation.

One way of estimating the total number of tektites in the Australasian strewnfield is to assume that the average density of fall is about 1 tektite per square meter. This density is perhaps a fair estimate for the Port Campbell sites of Victoria and for the Anda area of the Philippines, too high for areas such as the Malay Peninsula and Borneo, and not high enough for some parts of Java, Thailand and Indochina. The estimated total area of the known extent of the strewnfield is about 20.7 million square kilometers, and the number of tektites in the Australasian strewnfield would be about  $2 \times 10^{13}$ . If the average weight of a tektite is 10 grams, the estimated total weight of tektite material would be about  $2 \times 10^{14}$  grams, or, assuming an average density of  $2.5 \text{ gm/cm}^3$ , the volume of tektite material would be about 0.1 cubic kilometers.

This estimate is probably much too high because the assumption that

tektites fell with a density equivalent to one per square meter, is based on the estimated density of tektites in limited individual areas where tektites are known to be relatively abundant. The average density of fall may be estimated for a large area, such as the drainage basin of Manila Bay, by assuming that most tektites which fell in the drainage basin have been concentrated in the tektite-producing sites of this area. This would provide a minimum estimate of the original density of tektites in this part of the strewnfield.

The number of tektites recovered in the Manila Bay area is probably about 100,000. At the Ortigas site, the most prolific of the known tektite localities, over 50,000 tektites have been found. At Pugad Babuy and Santa Mesa, the total number found is probably less than 10,000. A conservative estimate of the total number of tektites now left in the Manila Bay area would be of the order of 500,000. The area of the drainage basin of Manila Bay is approximately 10,500 square kilometers. This leads to an estimate of about one tektite per 20,000 square meters. If this estimate is applied to the entire strewnfield, it leads to a total of  $10^9$  tektites. The total amount of tektite material on this basis would be about  $10^{10}$  grams, equivalent to a volume of about  $4 \times 10^3$  cubic meters of tektite material.

Even the lower estimate of the abundance of tektites indicates that a large impact event would be necessary to produce the Australasian tektites. In an impact event only a fraction of a percent of the total ejecta

consists of glass and only a fraction of that glass would be represented by the Australasian tektites. The volume of tektites may represent less than  $10^{-6}$  of the total volume of ejecta from an impact crater, which would place a lower limit for the size of the crater at 4 cubic kilometers.

#### Source of tektites

There are no known terrestrial meteorite craters in the Australasian strewnfield large enough to serve as single or multiple sources for the probable volume of the Australasian tektites. It is important that not a single site visited yielded material that is transitional between terrestrial rocks and tektites. There is thus no evidence for terrestrial meteoritic impact origin for the Australasian tektites.

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THE CHEMICAL COMPOSITION OF SELECTED  
INDOCHINITES AND PHILIPPINITES

by Frank Cuttitta, E. C. T. Chao,  
and M. K. Carron

Introduction

This is the second of a series of progress reports dealing with the composition of tektites from the Australasian strewnfields. The objectives of detailed chemical study of these tektites are: (1) to determine the variation of the chemical composition of tektites from this vast strewnfield to evaluate the possibility that all the tektites were formed by a single event; (2) to determine whether the variation of chemical composition is related to patterns of fall (such a relationship might provide clues concerning the place of origin of tektites); (3) to examine variations in chemical composition of the tektites which might be the result of the processes by which tektites are formed.

The first report presented analytical data for australites and javanites (Cuttitta and others, 1964). New chemical analyses are presented here for the major constituents of 5 indochinites from Dalat, South Viet Nam and 13 philippinites from various localities in the Philippines (4 from Coco Grove, 5 from Isabella, and 4 from Santa Mesa) (tables 1-4). Analytical work (major and minor elements) on an additional 10 indochinites and 12 thailandites is in progress. These tektites were selected to

Table 1. New chemical analyses of selected indochinites from Dalat, South Viet Nam (in weight percent)<sup>1/</sup>

	<u>ID-13</u>	<u>ID-18</u>	<u>ID-108</u>	<u>ID-23</u>	<u>ID-36</u>
SiO <sub>2</sub>	73.8	73.3	73.3	73.3	72.7
Al <sub>2</sub> O <sub>3</sub>	12.4	12.5 <sub>1</sub>	12.4 <sub>5</sub>	12.4 <sub>5</sub>	12.5 <sub>2</sub>
Fe <sub>2</sub> O <sub>3</sub>	.58	.36	.40	.44	.57
FeO	4.27	4.65	4.92	4.82	5.05
MgO	2.22	2.43	2.65	2.75	3.06
CaO	1.86	1.92	1.90	1.92	1.89
Na <sub>2</sub> O	1.35	1.32	1.29	1.08	1.28
K <sub>2</sub> O	2.45	2.37	2.39	2.31	2.32
TiO <sub>2</sub>	.72	.69	.74	.72	.80
P <sub>2</sub> O <sub>5</sub>	.07	.06 <sub>4</sub>	.05 <sub>5</sub>	.09 <sub>0</sub>	.04 <sub>5</sub>
MnO	.08 <sub>5</sub>	.07 <sub>2</sub>	.08 <sub>5</sub>	.05 <sub>2</sub>	.10 <sub>5</sub>
TOTAL	99.81	99.72	100.18	99.93	100.34
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	5.32	5.52	5.87	5.79	6.19
N <sub>D</sub> <sup>2/</sup>	1.5051	1.5067	1.5082	1.5094	1.5119
Sp gr <sup>2/</sup>	2.42 <sub>6</sub>	2.43 <sub>1</sub>	2.44 <sub>7</sub>	2.45 <sub>0</sub>	2.45 <sub>2</sub>
Mag sus <sup>3/</sup>	6.85	7.03	7.88	7.52	N.D.
Fe <sub>2</sub> O <sub>3</sub> /FeO	.136	.077	.081	.091	.113

N.D. = not determined.

<sup>1/</sup> Arranged in order of increasing index of refraction.

<sup>2/</sup> Determined by Janet Littler ( $N_D = \pm 0.0004$ ).

<sup>3/</sup> Magnetic susceptibility ( $\chi$ ) by F. Senftle, where  $\chi = (---)10^{-6}$  emu/g.

Table 2. New chemical analyses of selected philippinites from Coco Grove, Philippines (in weight percent)<sup>1/</sup>

	<u>Pc-8</u>	<u>Pc-9</u>	<u>Pc-26</u>	<u>Pc-12</u>
SiO <sub>2</sub>	73.0	72.1	71.4	70.2
Al <sub>2</sub> O <sub>3</sub>	12.7	12.9	13.2	14.4
Fe <sub>2</sub> O <sub>3</sub>	.32	.42	.30	.61
FeO	4.33	4.29	4.46	4.65
MgO	2.10	1.92	2.16	2.41
CaO	2.76	3.14	3.27	3.28
Na <sub>2</sub> O	1.45	1.54	1.44	1.34
K <sub>2</sub> O	2.56	2.63	2.57	2.63
TiO <sub>2</sub>	.78	.82	.84	.82
P <sub>2</sub> O <sub>5</sub>	.05	.11	.06	.11
MnO	.10	.10	.11	.12
TOTAL	100.15	99.88	99.85	100.58
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	5.13	5.18	5.25	5.79
N <sub>D</sub> <sup>2/</sup>	1.5086	1.5107	1.5130	1.5168
Sp gr <sup>2/</sup>	2.44 <sub>1</sub>	2.45 <sub>4</sub>	2.44 <sub>8</sub>	2.47 <sub>9</sub>
Mag sus <sup>3/</sup>	N.D.	6.67	6.82	7.47
Fe <sub>2</sub> O <sub>3</sub> /FeO	.074	.098	.067	.105

N.D. = not determined.

<sup>1/</sup> Arranged in order of increasing index of refraction.

<sup>2/</sup> Determined by Janet Littler ( $N_D = \pm 0.0004$ ).

<sup>3/</sup> Magnetic susceptibility ( $\chi$ ) by F. Senftle, where  $\chi = (---)10^{-6}$  emu/g.

Table 3. New chemical analyses of selected philippinites from Isabella, Philippines (in weight percent)<sup>1/</sup>

	<u>PI-33</u>	<u>PI-68</u>	<u>PI-94</u>	<u>PI-50</u>	<u>PI-111</u>
SiO <sub>2</sub>	74.1 <sub>7</sub>	73.2	71.8	71.4	70.6 <sub>2</sub>
Al <sub>2</sub> O <sub>3</sub>	10.9 <sub>5</sub>	11.9 <sub>7</sub>	13.2 <sub>1</sub>	13.8 <sub>3</sub>	14.4 <sub>7</sub>
Fe <sub>2</sub> O <sub>3</sub>	.00	.23	.15	.22	.37
FeO	4.28	4.29	4.64	4.92	5.00
MgO	2.01	2.38	2.43	2.46	2.89
CaO	4.12	3.79	2.86	2.84	2.77
Na <sub>2</sub> O	1.32	1.19	1.38	1.24	.97
K <sub>2</sub> O	2.20	2.19	2.39	2.42	2.11
TiO <sub>2</sub>	.65	.70	.78	.79	.82
P <sub>2</sub> O <sub>5</sub>	.07	.07	.10	.08	.07
MnO	.10	.11	.11	.11	.11
TOTAL	99.87	100.12	99.85	100.32	100.20
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	4.72	4.98	5.37	5.69	5.93
N <sub>D</sub> <sup>2/</sup>	1.5081	1.5107	N.D.	1.5133	1.5154
Sp gr <sup>2/</sup>	2.44 <sub>2</sub>	2.43 <sub>8</sub>	N.D.	2.45 <sub>8</sub>	2.47 <sub>3</sub>
Mag sus <sup>3/</sup>	6.76	6.84	N.D.	7.15	7.21
Fe <sub>2</sub> O <sub>3</sub> /FeO	.00	.054	.032	.045	.074

N.D. = not determined.

<sup>1/</sup> Arranged in order of increasing index of refraction.

<sup>2/</sup> Determined by Janet Littler (N<sub>D</sub> = ± 0.0004).

<sup>3/</sup> Magnetic susceptibility (χ) by F. Senftle, where χ = (---)10<sup>-6</sup> emu/g.

Table 4. New chemical analyses of selected philippinites from Santa Mesa, Philippines (in weight percent)<sup>1/</sup>

	<u>Ps-46</u>	<u>Ps-17</u>	<u>Ps-11</u>	<u>Ps-135</u>
SiO <sub>2</sub>	73.0 <sub>5</sub>	72.68	72.0	70.7 <sub>7</sub>
Al <sub>2</sub> O <sub>3</sub>	12.5 <sub>0</sub>	12.7 <sub>9</sub>	13.1 <sub>8</sub>	13.5 <sub>7</sub>
Fe <sub>2</sub> O <sub>3</sub>	.40	0.25	.34	.56
FeO	4.17	4.38	4.49	4.45
MgO	2.31	2.36	2.66	2.93
CaO	2.80	2.73	2.69	2.89
Na <sub>2</sub> O	1.29	1.24	1.20	1.32
K <sub>2</sub> O	2.32	2.33	2.35	2.39
TiO <sub>2</sub>	0.75	0.75	.77	.85
P <sub>2</sub> O <sub>5</sub>	.09	.08	.08	.10
MnO	.08 <sub>6</sub>	.09 <sub>5</sub>	.10 <sub>4</sub>	.09 <sub>3</sub>
TOTAL	99.77	99.69	99.86	99.92
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	5.03	5.11	5.33	5.51
N <sub>D</sub> <sup>2/</sup>	1.5084	1.5101	1.5127	1.5160
Sp gr <sup>2/</sup>	2.42 <sub>7</sub>	2.44 <sub>1</sub>	2.46 <sub>3</sub>	2.43 <sub>4</sub>
Mag sus <sup>3/</sup>	N.D.	6.45	N.D.	N.D.
Fe <sub>2</sub> O <sub>3</sub> / FeO	.096	.057	.076	.102

N.D. = not determined.

<sup>1/</sup> Arranged in order of increasing index of refraction.

<sup>2/</sup> Determined by Janet Littler ( $N_D = \pm 0.0004$ ).

<sup>3/</sup> Magnetic susceptibility ( $\chi$ ) by F. Senftle, where  $\chi = (---)10^{-6}$  emu/g.

represent approximately the entire range of indices of refraction and specific gravities exhibited by a collection of about 1300 indochinites, 1500 thailandites, and more than 10,000 philippinites.

For comparative purposes, the new data have been combined with previous data in tables 5 and 6. Data on minor elements (Ag, B, Ba, Be, Co, Cr, Cs, Cu, Ga, La, Li, Mn, Nb, Ni, Pb, Rb, Sc, Sr, V, Y, and Zr) for the newly analyzed Australasian tektites were presented in the previous report (Cuttitta and others, 1964, p. 30-46) and by Annell and others (1964). A statistical analysis of the chemical data is being programmed to evaluate the correlations of major and minor elements in the tektites.

#### Chemical composition of selected Australasian tektites

The analyses indicate a gross similarity of elemental abundances in all Australasian tektites. The ranges of silica content of various tektite suites from this strewnfield (72.7-73.8 indochinites, 69.06-74.2 philippinites, 72.3-74.4 javanites, and 71.2-78.0 australites) show considerable overlap (tables 5 and 6). This is also true for specific gravity and index of refraction (tables 1-4). FeO varies inversely with respect to  $\text{SiO}_2$  in australites, philippinites, indochinites, and javanites. These similarities suggest that all Australasian tektites are derived from the same or similar parent rock materials, possibly by a single event. This conclusion is in agreement with the concordant 700,000 year K/Ar ages of tektite suites of various parts of this strewnfield (Zähringer, 1963).

Table 5. Ranges of the major oxides and the average composition of analyzed javanites and indochinites (in percent)<sup>1/</sup>

	<u>Javanites</u>		<u>Indochinites</u>	
	<u>Range</u>	<u>Average (6)</u>	<u>Range</u>	<u>Average (5)</u>
SiO <sub>2</sub>	72.3 - 74.4	73.42	72.7 - 73.8	73.28
Al <sub>2</sub> O <sub>3</sub>	11.1 - 11.4	11.28	12.4 - 12.5	12.47
Fe <sub>2</sub> O <sub>3</sub>	0.27 - 0.56	0.40	.36 - .58	.47
FeO	4.47 - 5.25	4.80	4.27 - 5.05	4.74
MgO	2.88 - 3.79	3.27	2.22 - 3.06	2.62
CaO	2.25 - 2.91	2.63	1.86 - 1.92	1.90
Na <sub>2</sub> O	1.17 - 1.26	1.23	1.08 - 1.35	1.26
K <sub>2</sub> O	2.17 - 2.29	2.24	2.31 - 2.45	2.37
TiO <sub>2</sub>	0.67 - 0.70	0.68	.69 - .80	0.73
P <sub>2</sub> O <sub>5</sub>	0.06 - 0.07	0.06	.04 - .09	0.06 <sub>4</sub>
MnO	0.09 - 0.11	0.10	.05 - .11	0.08 <sub>0</sub>
TOTAL		100.11		99.98
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	5.26 - 6.50	5.72	5.32 - 6.19	5.74
N <sub>D</sub>	1.5065- 1.5141	1.5098	1.5051- 1.5119	1.5083
Sp gr	2.42 <sub>6</sub> - 2.48 <sub>3</sub>	2.45 <sub>4</sub>	2.42 <sub>6</sub> - 2.45 <sub>2</sub>	2.44 <sub>1</sub>
Mag sus emu/g	(6.39 - 8.09)10 <sup>-6</sup>	(7.30)10 <sup>-6</sup>	(6.85 - 7.88)10 <sup>-6</sup>	(7.32)10 <sup>-6</sup>
Fe <sub>2</sub> O <sub>3</sub> /FeO	.056- .120	.083	.077- .136	0.010

<sup>1/</sup> Includes analyses (javanites) reported by Cuttitta and others (1964).

Table 6. Ranges of the major oxides and the average composition of analyzed australites and philippinites (in percent)<sup>1/</sup>

	<u>Australites</u>		<u>Philippinites</u>	
	<u>Range</u>	<u>Average (6)</u>	<u>Range</u>	<u>Average (17)</u>
SiO <sub>2</sub>	71.2 - 78.0	74.7	69.0 - 74.2	71.74
Al <sub>2</sub> O <sub>3</sub>	10.3 - 12.4	11.5	11.0 - 14.7	13.13
Fe <sub>2</sub> O <sub>3</sub>	0.20 - 0.48	.31	.00 - .61	.29
FeO	3.61 - 4.23	3.94	4.17 - 5.28	4.57
MgO	1.34 - 1.94	1.74	1.92 - 2.93	2.41
CaO	2.24 - 5.58	3.77	2.69 - 4.12	3.10
Na <sub>2</sub> O	1.15 - 1.22	1.18	0.97 - 1.54	1.33
K <sub>2</sub> O	2.09 - 2.25	2.17	2.11 - 2.63	2.37
TiO <sub>2</sub>	0.62 - 0.74	0.68	0.65 - 0.87	.78 <sub>5</sub>
P <sub>2</sub> O <sub>5</sub>	0.03 - 0.06	0.05	0.04 - 0.11	.08 <sub>1</sub>
MnO	0.08 - 0.12	0.09	0.08 - 0.11	.10 <sub>1</sub>
TOTAL		100.13		99.91
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	4.28 - 5.18	4.68	4.72 - 5.93	5.37
N <sub>D</sub>	1.4970- 1.5190	1.5078	1.5081- 1.5169	1.5122
Sp gr	2.39 <sub>5</sub> - 2.47 <sub>6</sub>	2.43 <sub>1</sub>	2.42 <sub>7</sub> - 2.47 <sub>9</sub>	2.45 <sub>0</sub>
Mag sus emu/g	(5.45 - 6.83)10 <sup>-6</sup>	(6.12)10 <sup>-6</sup>	(6.45 - 9.29)10 <sup>-6</sup>	(6.92)10 <sup>-6</sup>
Fe <sub>2</sub> O <sub>3</sub> /FeO	.052 - .114	.078	<.0000 - .105	.061

<sup>1/</sup> Includes analyses of australites and philippinites reported by Cuttitta and others (1964).



The detailed analyses, however, reveal a clear distinction between two groups of tektites: (1) indochinites and javanites, and (2) philippinites and australites. Indochinites and javanites have MgO in excess of CaO, whereas philippinites and australites are characterized generally by CaO in excess of MgO. In indochinites and javanites the alumina is not correlated with silica, whereas the alumina content in philippinites and australites varies inversely with the silica content (tables 1 and 5). Finally, the Co, Cr, and Ni contents in indochinites and javanites are notably higher than in philippinites and australites (Ansell and others, 1964). The philippinites and australites appear to form a distinct group lying to the east of the indochinites and javanites.

This pattern is not yet fully explored and is probably more complex than so far indicated. For example, some of the philippinites with MgO content nearly equal or slightly greater than CaO (Pi-111, table 3, Ps-11, Ps-135, table 4) seem to be more closely related to the indochinites. Some differences in composition are found within the indochinite-javanite group. Javanites show a negative correlation between silica and lime and a positive correlation between lime and magnesia, whereas indochinites do not show these relationships.

It is hoped that the chemical characteristics will help reveal a pattern of fall which can be correlated with temperature of heating of the tektite melt and possibly the time or sequence of arrival within the Australasian strewnfield. The detailed chemical data when integrated with

data on ablation characteristics of Australasian tektites and calculated trajectories should yield a more comprehensive insight into the origin of the strewnfield.

### Conclusions

The pattern of correlation between elements in the newly analyzed indochinites and philippinites is similar to that found in the javanites and australites (Cuttitta and others, 1964). Philippinites resemble australites and indochinites resemble javanites. The new data support the conclusions based on the earlier analyses:

1. Australasian tektites comprise at least two distinct chemical populations: (1) the indochinites and javanites, and (2) the australites and philippinites. Among other characteristics, the MgO-CaO ratio generally exceeds 1 in the first group and is less than 1 in the second.
2. Variation of the more or less volatile constituents in Australasian tektites supports the hypothesis of selective loss of these constituents by volatilization under reducing conditions during tektite formation.
3. The source material for all of the Australasian tektites had a range of composition typical of certain terrestrial silicic igneous rocks.

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A COMPARISON OF TWO SOLUTION TECHNIQUES USED IN EMISSION  
SPECTROSCOPY: THE GAS CONTROLLED ARC AND  
ROTATING DISC-HIGH VOLTAGE SPARK

by Charles Annell

Introduction

This report is part of a continuing investigation into the application of spectrographic analyses to small samples. Since the last report concerning the rotating disc electrode method for spectrographic analysis of solutions (Annell, 1964), the gas controlled arc method has been tested and a comparison of the two techniques can be made.

Analytical techniques

Rotating disc-high voltage spark--The rotating disc electrode assembly used for the spectrographic analysis of solutions consists of a graphite disc, 0.5 inch in diameter and 1/8 inch thick, affixed to the end of a horizontal, motor-driven shaft (Hyman, 1962). The disc rotates at about 30 revolutions per minute, partially submerged in the sample solution contained in a porcelain boat. The wet disc brings the sample continuously into a position opposite a 1/8-inch graphite rod electrode maintained 4 mm above the disc. A high voltage spark discharged 240 times a second excites the sample. The spark emission is focussed on a 25-micron slit with a cylindrical quartz lens with a focal length of 100 cm. An emulsion (III-0) records the spectrum in the

ultraviolet region.

Approximately half of a 2-ml sample is used in each run. The electrode and solution become heated during the discharge, causing some evaporation of the remaining solution. For replicate exposures a fresh 2-ml sample is necessary to prevent erratic results.

Gas controlled arc.--A recently developed gas controlled arc, also referred to as the "plasma arc" or "plasma jet" (Margoshes and Scribner, 1959; Owen, 1961) has become available commercially. The arc assembly consists primarily of a gas manifold which regulates a He gas flow that directs the arc flame from a graphite ring anode through a graphite ring cathode to an external tungsten rod cathode. Liquid samples are introduced through the anode ring by a Beckman medium bore atomizer using an argon gas siphon. The sample is aspirated through the atomizer from a small plastic container.

He gas is introduced into the gas jet assembly tangentially, and is maintained at a flow rate of 45 cubic feet per hour. The argon gas is adjusted at 4.5 cubic feet per hour for a sample consumption of slightly over 1 ml per minute. A direct current of 20 amperes gives a stable arc. These adjustments may be varied slightly, but a rather small variation in any one may introduce an instability in the arc.

The middle third of the arc, between the graphite cathode orifice and the tungsten rod cathode, is focussed on the slit with a 100-cm focal length spherical quartz lens. Exposures were 60 seconds at

100 percent transmission. An emulsion (III-O) recorded the spectra in the wavelength region between 2250 and 4750 Å.

The spectra with the gas controlled arc have some interference from OH bands, which are most intense from about 2810 to 3250 Å. These bands preclude use of spectral lines of coinciding wavelengths, and, in addition, they often create high backgrounds, thereby introducing a source of error.

#### Comparison of the two methods

A test of the accuracy and precision of the gas controlled arc was made with a group of well analyzed silicate rock standards prepared in a 3 percent  $\text{HClO}_4$  solution. The silica was driven off as  $\text{SiF}_4$  during dissolution of the standards in a  $\text{HF-HClO}_4$  mixture. The remaining HF was removed by bringing the solution to fumes of  $\text{HClO}_4$ , and the final  $\text{HClO}_4$  concentration was adjusted to 3 percent by volume. The sample solutions contained either 0.25 mg or 0.50 mg of silicate per ml, 1 mg/ml  $\text{K}_2\text{CO}_3$  as a spectrographic buffer and 1 mg/ml Co (as  $\text{CoCl}_2$ ) as an internal standard.

Five standard solutions of synthetic tektite compositions prepared in the same manner as the sample solutions were used to obtain analytical curves in the usual way (American Society for Testing Materials, 1964). The concentration ranges covered by the analytical curves for the five

elements is shown in table 1. These ranges were selected because they bracketed the concentrations in the samples being analyzed.

All spectra were made with 60-second exposures in which approximately 1 ml of solution was used. The concentration of Js-5, W-1, and ST-1 was 0.25 mg/ml, and of G-1 and G-W was 0.50 mg/ml. Results of duplicate exposures for five elements in rock and tektite samples are shown in table 2. For comparison, analytical results obtained for javanite, Js-5, by the rotating disc method (Annell, 1964) are also included in table 1.

A comparison of analytical results obtained for Philippine tektites using the two solution techniques is shown in table 3. The values listed are the average, in percent, of at least three chemical (or X-ray) determinations, the average of two spectrographic determinations and the relative percent difference between spectrographic and chemical results.

Exposure time for the rotating disc method is 120 seconds and for the gas controlled arc method, 60 seconds. The amount of sample solution consumed during a 120-second exposure is 2 ml and for the gas controlled arc method, 1 ml. Duplicate exposures requiring 4 ml of solution in the rotating disc method and 2 ml in the gas controlled arc method require 1.0 and 0.5 mg of sample, respectively. In spectra with similar backgrounds, the relative line intensities obtained with the rotating disc are 5 to 10 times greater. Increased exposure time for the gas controlled arc will increase the intensity of both line and background proportionately and will not contribute to greater detectability.

Table 1. Percent range of concentration used for determining Al, Ca, Fe, Mg, and Ti in silicate rocks by the solution spectrographic methods, based on synthetic tektite (or silicate) standards equivalent to 0.25 mg tektite/ml solution.

<u>Methods</u>	<u>Al</u>	<u>Ca</u>	<u>Fe</u>	<u>Mg</u>	<u>Ti</u>
Rotating Disc-High Voltage Spark	1-10	0.1-5	0.5-10	0.1-5.0	0.1-5.0
Gas-Controlled Arc	1-10	0.3-5	0.5-10	0.1-5.0	0.2-5.0

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Note: The lower concentrations do not represent limits of detectability. In most cases this limit is at a lower undetermined concentration.



Table 2. Comparison of analytical data obtained by gas controlled arc and rotating disc-high voltage spark techniques, with chemical results (in percent element)

Element - Line pair	<u>Al</u> <u>3961.5</u> <u>Co</u> <u>3997.9</u>		<u>Ca</u> <u>4226.7</u> <u>Co</u> <u>3997.9</u>		<u>Fe</u> <u>2599.4</u> <u>CoII</u> <u>2632.2</u>		<u>Mg</u> <u>2852.1</u> <u>Co</u> <u>3061.8</u>		<u>TiII</u> <u>3234.5</u> <u>Ti</u> <u>CoII</u> <u>2632.2</u>	
<u>Samples</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>
Js-5 (Java ) <sup>1,3/</sup> (tektite)	5.6, 5.8	6.1	1.72, 1.92	1.86	3.7, 3.6	3.70	1.62, 1.64	1.83	0.43, 0.51	0.40
G-1 (granite) <sup>1/</sup>	7.6, 7.5	7.7	0.95, 0.91	1.01	1.28, 1.32	1.44	0.22, 0.24	0.25	0.23, 0.22	0.16
G-W (granite+ ) <sup>1/</sup> (diabase 1:1)	7.6, 8.1	7.9	4.2, 4.3	4.42	4.4, 4.4	4.61	1.95, 2.15	2.07	0.46, 0.42	0.45
W-1 (diabase) <sup>1/</sup>	7.2, 8.6	8.1	7.8, 9.0	7.82	7.5, 7.3	7.77	4.0, 4.2	3.90	0.80, 0.77	0.75
ST-1 (synthetic) <sup>1,3/</sup> (Texas ) (tektite )	6.6, 7.2	7.4	0.58, 0.76	0.72	1.64, 1.80	1.75	0.92, 1.00	1.00	0.43, 0.60	0.36
Element - Line pair	<u>Al</u> <u>3082.2</u> <u>Co</u> <u>3354.1</u>		<u>CaII</u> <u>3179.3</u> <u>Co</u> <u>3322.2</u>		<u>FeII</u> <u>2599.4</u> <u>CoII</u> <u>2405.4</u>		<u>Mg</u> <u>2852.1</u> <u>Co</u> <u>3322.2</u>		<u>TiII</u> <u>3234.5</u> <u>Ti</u> <u>CoII</u> <u>2632.2</u>	
<u>Sample</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>	<u>Spec</u>	<u>Chem</u>
Js-5 (Java ) <sup>2,3/</sup> (tektite)	6.3, 6.4	6.1	1.9, 1.8	1.9	3.8, 4.0	3.7	1.8, 1.9	1.8	0.49, 0.50	0.40

<sup>1/</sup> Gas-controlled arc

<sup>2/</sup> Rotating disc-high voltage spark

<sup>3/</sup> Chemical and X-ray fluorescent analyses by Frank Cuttitta and Maxwell K. Carron



Table 3--Continued. Comparison between average chemical (or X-ray fluorescent) and spectrographic values for two solution-spectrographic techniques applied to some philippinites

<u>Methods</u>	<u>Element- Line Pair</u>	<u>Mg 2852.1</u> <u>Mg Co 3322.2</u>				<u>TiII 3234.5</u> <u>Ti Co 3322.2</u>			
		<u>Sample</u>	<u>Spec</u>	<u>Chem</u>	<u>Diff%</u>	<u>Spec</u>	<u>Chem</u>	<u>Diff%</u>	
Rotating Disc-High Voltage Spark		Ps- 11	1.4	1.5	-6.7	.48	.46	+4.4	
		Ps- 17	1.6	1.4	+14	.52	.45	+16	
		Ps-135	1.8	1.9	-5.3	.52	.47	+11	
		Ps- 46	1.6	1.5	+6.7	.52	.44	+18	
	<u>Element- Line Pair</u>	<u>Mg 2852.1</u> <u>Mg Co 3061.8</u>				<u>TiII 3234.5</u> <u>Ti CoII 2632.2</u>			
		<u>Sample</u>	<u>Spec</u>	<u>Chem</u>	<u>Diff%</u>	<u>Spec</u>	<u>Chem</u>	<u>Diff%</u>	
Gas Controlled Arc		P <sub>I</sub> -33	1.3	1.2	+ 8.3	.42	.39	+ 7.7	
		P <sub>I</sub> -68	1.7	1.4	+21	.47	.42	+12	
		P <sub>I</sub> -50	1.5	1.5	0	.53	.47	+13	
		P <sub>I</sub> -94	1.5	1.5	0	.52	.47	+11	
		P <sub>I</sub> -111	1.9	1.7	+12	.54	.49	+10	

### Conclusions

Comparison of the two solution-spectrographic methods can be summarized by these points:

(1) The accuracy and precision of the two methods are similar. No decided choice between the methods is indicated by the data given in tables 2 and 3. Comparison between the spectrographic and chemical (or X-ray) determinations shows an average difference of less than 10 percent for Al, Ca, Fe, and Mg. The Ti results are regularly higher by spectrographic methods and may indicate a need for new Ti standards.

(2) The larger volume of solution consumed by the rotating disc method is offset by greater line intensity and increased detectability. This greater detectability obtained with the rotating disc electrode recommends its use with a wider variety of silicate rock samples.

(3) Both solution techniques can be used to advantage when major element determinations are required on 1-5 mg of silicate rock.

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QUANTITATIVE SPECTROGRAPHIC DETERMINATION OF Na AND K IN  
SILICATE ROCK SOLUTIONS USING THE ROTATING  
DISC AND HIGH VOLTAGE SPARK

by Charles Annell

Introduction

A previous report on the use of the rotating disc and high voltage spark spectrographic technique described the determination of Al, Fe, Mg, Ca, and Ti in solutions containing milligram and submilligram quantities of silicate, including tektite samples (Annell, 1964). At the time of the previous report, the determination of Na and K was also tried, but proved unsuccessful. This report describes the successful determination of Na down to 0.1 percent and K down to 0.3 percent in 0.5 mg samples by the rotating disc method.

The rotating disc electrode with high voltage spark excitation is frequently used for the analyses of solutions or liquids. For a description of apparatus used in this work see Annell (this report) and Hyman (1962). Solutions were prepared with a  $\text{HClO}_4$ -HF mixture. The Si was volatilized as  $\text{SiF}_4$  and the solution heated to  $\text{HClO}_4$  fumes to eliminate excess HF. The solution was then adjusted to 3 percent  $\text{HClO}_4$  by volume and contained 0.5 or 1.0 mg of sample per ml of solution.

Use of normal conditions and procedures proved unsuccessful for analyzing small amounts of Na and K. The very sensitive Na 5890.0 and

K 7664.9 lines were photographed using a red-sensitive I-N emulsion. An ultraviolet absorbing filter was required at the slit to avoid second and third order line interferences at these long wavelengths. With a 25-micron slit, under these conditions, 1 percent Na and K were barely detectable at a sample concentration of 1 mg/ml of solution; furthermore, the slopes of the analytical curves were too low for use in quantitative analysis.

#### New analytical procedure

By experimentation, a 60-micron slit width was found to provide the maximum illumination with low density background in the 5500-8000 Å region. The 25-micron slit used normally, while desirable for the ultraviolet region where sensitive lines of Al, Fe, Mg, Ca, and Ti are located, is not wide enough to fill the spectrographic collimator with light of these higher wavelengths (Harrison and others, 1948).

An effective spectrographic buffer and internal standard element were added to the sample solutions in order to control intensity changes due to variations in the sample matrix, excitation, developing, or emulsion. The buffer used consisted of 1 mg RbCl (Specpure) per ml of solution. The RbCl necessarily had to be free of detectable K and Na contamination. The internal standard consisted of 0.05 mg  $\text{Li}_2\text{CO}_3$  per ml of solution.

The grating spectrograph used for these determinations requires separate settings for Na and K at the higher wavelengths, and Al, Fe,

Mg, Ca, and Ti at the lower wavelengths. This necessitates two separate exposures in order to determine all seven elements. If 2 ml of solution is used per exposure, the two exposures require a minimum of 1 mg of sample.

### Results

Analytical curves obtained from the synthetic tektite standards and G-1 and W-1 silicate standards are given in figures 1 and 2. The  $\frac{\text{Na } 5890.0}{\text{Li } 6707.8}$  and  $\frac{\text{K } 7664.9}{\text{Li } 6707.8}$  intensity ratios are plotted against the percent alkali in the original silicate sample. Slopes of the analytical curves are close to 45 degrees, which permits accurate determinations that had been impossible without the Li internal standard and RbCl buffering. The rotating disc-high voltage spark technique of solution analysis, with the proper buffer and internal standard, can be used to quantitatively determine at least 0.1 percent Na and 0.3 percent K in a 0.5 mg silicate sample.

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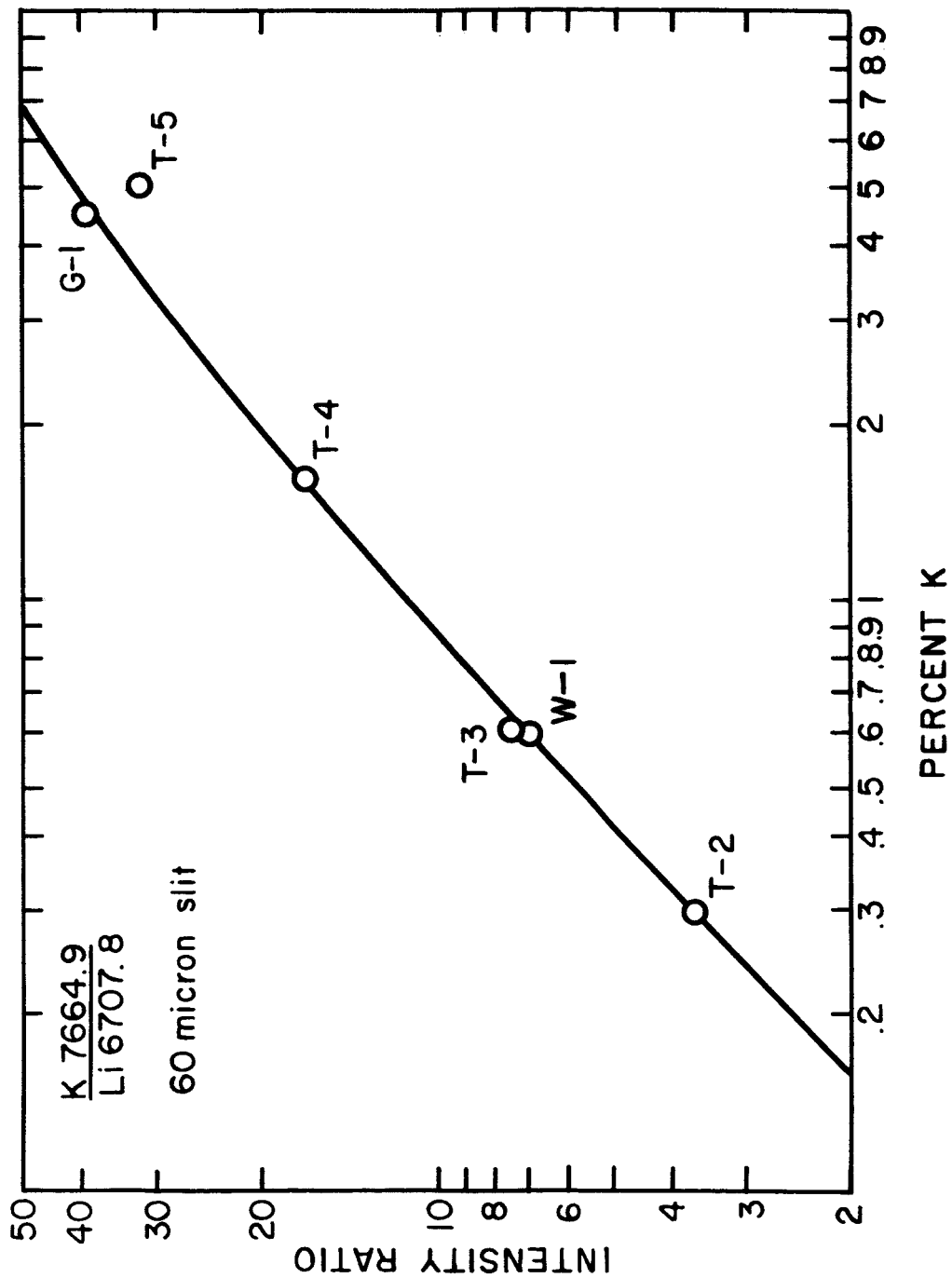


Figure 1. Analytical curve for the determination of Na in 3.97 perchloric acid solution of silicate rocks using the rotating disc-high voltage spark method. Percent values refer to the Na content of the original silicate rock.

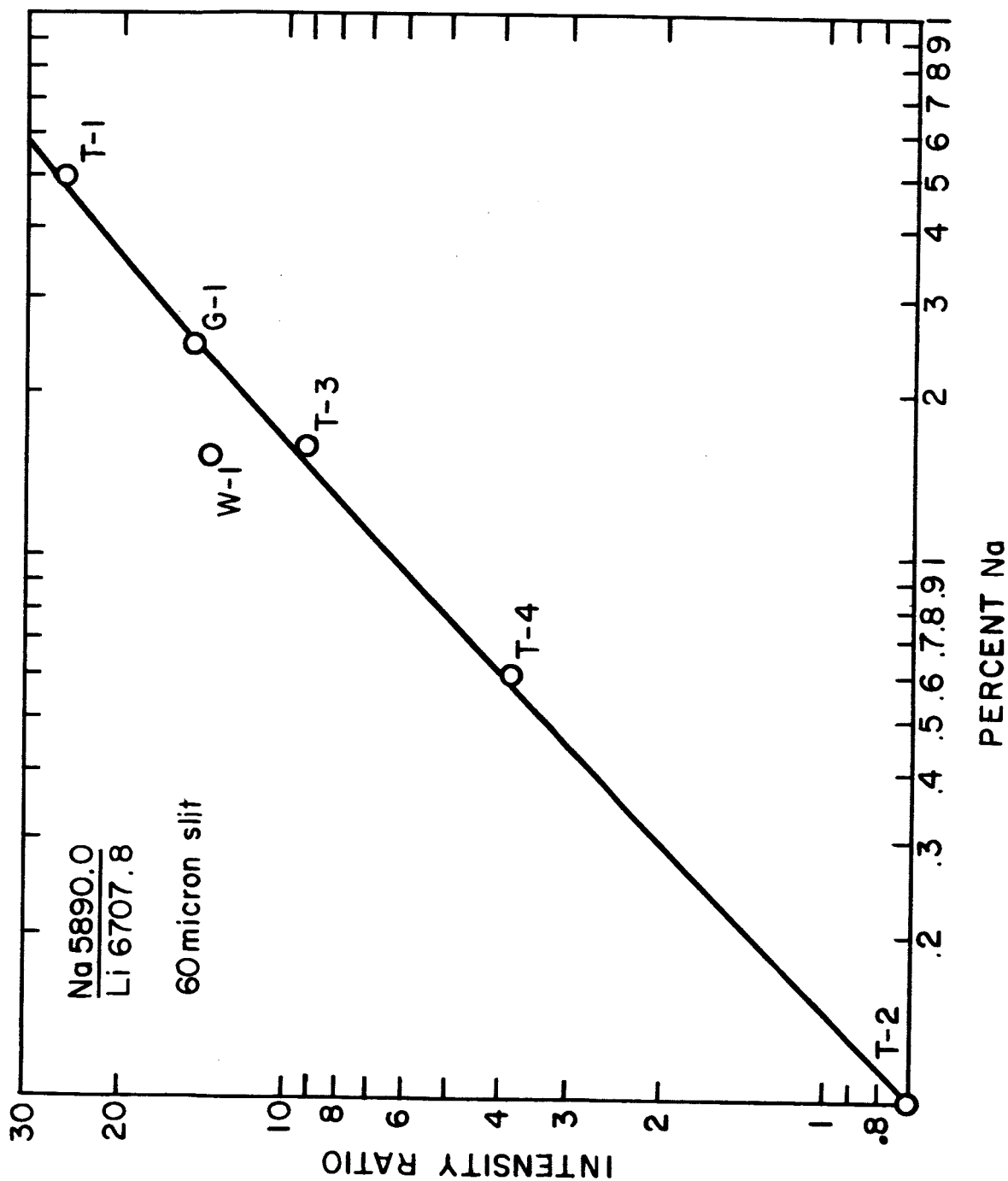


Figure 2. Analytical curve for the determination of K in 3.97 perchloric acid solutions of silicate rocks using the rotating disc-high voltage spark method. Percent values refer to the K content of the original silicate rock.

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NEW COMPOSITIONAL DATA ON METALLIC  
SPHERULES FOUND IN PHILIPPINE TEKTITES

by F. C. Cuttitta, E. C. T. Chao,  
and Charles Annell

Introduction

This preliminary report presents qualitative compositional data obtained by neutron activation analyses of a group of three metallic spherules found in a philippinite (Po-3) from the Ortigas Site, near Manila, Luzon. Other qualitative data were obtained on a single spherule by emission spectroscopy using an optical laser microprobe. The analyzed metallic spherules, discovered in wafers cut from the greenish pale-brown philippinites, ranged from 200 to 450 microns in diameter.

The occurrences and mineralogic, petrologic, and nickel-iron data on metallic spherules discovered embedded in philippinites from the Ortigas Site of Mandaluyong near Manila and in indochinites of Dalat, South Viet Nam, have been previously reported by Chao and co-workers (1962, 1964). They reported that the metallic spherules found embedded in tektites resemble fresh meteoritic spheroids from Meteor Crater, Arizona, in texture and mineral assemblage. By means of a micro-focus X-ray diffraction unit and the study of polished sections, a network of schreibersite with some troilite in a kamacite (Fe-Ni) matrix was identified (Chao and others, 1964). Their electron-probe micro-analysis of the kamacite and

schreibersite in the metallic spherules provided quantitative analytical data for Fe, Ni, and P. These data produced consistently low summations, suggesting the presence of other elements not detectable by spot analysis, as scanning of various areas of the spherule detected only Fe, Ni, P, S, and traces of Co.

A meteorite impact mechanism has been proposed for the formation of the nickel-iron spherules found in tektites. According to this hypothesis molten droplets of an impacting meteorite body are dispersed in the tektite melt formed by shock-induced fusion of the target rocks (Chao and others, 1962 and 1964). Metallic nickel-iron and various sulfide minerals occurring in meteorites contain siderophilic and chalcophilic elements in great abundance compared to silicate rocks. If the meteorite impact hypothesis is valid, the distinctive minor element assemblage of the iron meteorites might be found in the metallic spherules of the tektites. Thus, trace element analyses may provide not only additional compositional description of the nickel-iron spherules but also further evidence supporting a meteoritic impact hypothesis as the mechanism for the formation of tektites.

#### Emission spectroscopic analysis

A metallic spherule in a philippinite (Po-3c) from the Ortigas Site, was qualitatively analyzed by emission spectroscopy using an optical ruby laser microprobe. The spherule was embedded in a suitable epoxy resin and

carefully polished by hand and by vibratory polishing equipment. Absorption by the sample of the laser beam, which is concentrated on the sample by the objective lens of a microscope, results in vaporization of the target over all of the area exposed to the beam. The vaporized sample (from a 50-micron diameter laser crater) short circuits an auxiliary electrical gap positioned between the sample and the microscope objective. The resultant discharge produces a useful spectral emission of the spherule material, which is recorded in a one-shot process with an equivalent exposure time in the millisecond range. Selection of the spherule area to be analyzed was accomplished by adjustment of cross hairs as the specimen was viewed through the eyepiece of an inverted metallurgical microscope. For comparison, spectra of several areas of the embedding epoxy were also obtained.

Individual spectra are not representative of any determinable quantity of the sample. This is due to variations in the optical density of the material being sampled, small irregularities in the geometry of the surface being sampled, and unavoidable variations in the electrode gap and its distance from the sample. As the laser pit has a hemispherical shape about 50 microns in diameter, it represents the volatilization of the order of one microgram of sample.

A qualitative analysis of the elemental spectra and the related emission intensities showed the presence of readily detectable quantities of Cu, Fe, and Mg; less intense spectra of Al, Ca, Pb, and Ni; and faint traces of Ba, Si, Ag, and Ti in the spherule.

### Neutron activation analyses

Three spherules were simultaneously irradiated for 16 hours in a teflon capsule at the Atomic Energy Commission X-10 reactor facilities at Oak Ridge, Tennessee, which has a usable thermal neutron flux of  $5 \times 10^{11}$  neutrons  $\text{cm}^{-2} \text{sec}^{-1}$ . The radioactive spherules were transferred to a non-radioactive polyethylene container, and the gamma activity was counted in a 400-channel gamma-ray spectrometer equipped with a 3 inch by 3 inch sodium iodide (thallium activated) crystal and a photomultiplier.

Evaluation of the gamma-ray spectra of the irradiated spherules provided data that can be best interpreted as indicating the probable presence of Sb and Ir (siderophilic); Mo, Ag, and Zn (chalcophilic); and Mn (lithophilic) as minor constituents of the metallic spherules. The presence in the nickel-iron spherules of a suite of trace elements similar to those found in materials of known meteoritic origin (Goldschmidt, 1954; Heide, 1964; Mason, 1958) is consistent with a meteorite impact origin for tektites.

A comparison of the nickel-iron spherules found embedded in Asian tektites with metallic spherules of known impact origin from the Meteor Crater, Arizona, and the Wabar Crater, Saudi Arabia, is now in progress using neutron activation techniques.

### Acknowledgment

We are indebted to Dr. Frederick Brech of Jarrell-Ash Company, Newtonville 60, Massachusetts, for his co-operation and help in providing the laser microprobe instrumentation used in this study. We are also indebted to the Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tennessee, for the use of their instrumental facilities.

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SOME ALKALI AND TITANIA ANALYSES OF TEKTITES BEFORE  
AND AFTER G-1 PRECISION MONITORING

by D. B. Tatlock

Determination of the accuracy of chemical analyses of rocks has always been difficult. The earliest approach (Washington's tables, 1917) was, in large part, simply to examine the summation of individual analyses. More recently, information on the accuracy of rock analysis has been gained through the study of the precision of replicate analyses of standard samples, especially G-1 and W-1 (Schlecht and Stevens, 1951; and Stevens and Niles, 1960). A third approach to determining the accuracy of rock analyses is to examine to what extent analyses of different but closely related samples show systematic rather than random patterns of variation of compositional properties. An excellent opportunity for this is provided by comparing modern precisely monitored analyses of Australasian tektites with older analyses of specimens collected from the same strewnfield.

Since 1961, 98 complete and 12 partial chemical analyses of major elements of Australasian tektites have appeared in the geologic literature (16, Barnes, 1964; 4, Cuttitta and others, 1962; 12, Cuttitta and others, 1964; 34, Schnetzler and Pinson, 1964; 24, Taylor, 1962; 19, Taylor and Sachs, 1964; and 1, Wilford and Barnes, 1964). All were precisely monitored with various standards which included G-1 granite, W-1 diabase,

NBS 99 (feldspar), and artificial tektite glasses. These modern analyses allow for a reasonable petrochemical grouping of Australasian tektites based largely on modified ACF and AKF plots (report in progress).

In contrast, no such reasonable grouping can be made from one partial and 54 complete analyses of Australasian tektites that appeared in the literature from 1897 to 1956. (Forty-seven analyses were compiled by Barnes, 1940, and 8 by Schnetzler and Pinson, 1963.) This is due in large part to probable inaccuracies in CaO and MgO determinations, especially in the older indochinite and javanite analyses, as pointed out by Cuttitta and others (1962, 1964) and Schnetzler and Pinson (1963). So far as I know, however, no one has discussed the probable gross inaccuracies in the alkali oxide and  $\text{TiO}_2$  determinations in the older analyses as compared with the modern, precisely monitored analyses. On the contrary, Schnetzler and Pinson (1964, p. 798) have stated that, except for MgO and CaO, "There appears to be general agreement between Schnetzler's analyses and the analyses reported by Barnes (1940)."

Probably the most striking characteristic of the 110 modern analyses, and possibly the most important as regards the derivation of tektites, is the remarkable constancy of the alkali ratios and of the total alkali--this despite a rather wide range in CaO,  $\text{Al}_2\text{O}_3$ , and (FeO+MgO). Figure 1 shows the variation of  $\text{K}_2\text{O}$  with respect to  $\text{Na}_2\text{O}$  in the modern analyses. The Niggli k-values range from 0.48 to 0.58 and average 0.53; this is about the maximum k-value range found in unaltered salic vitrophyres and

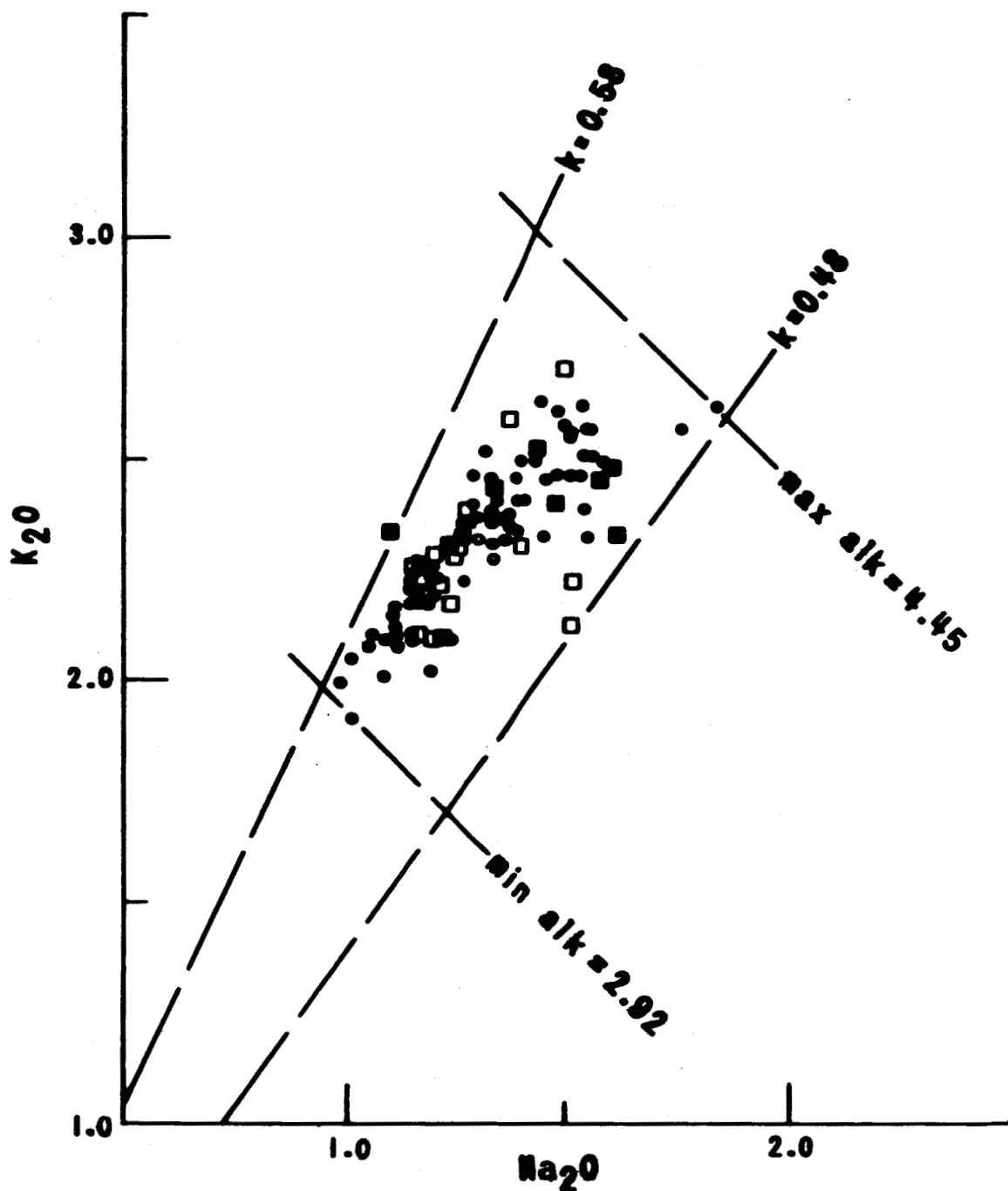


Figure 1. Variation of  $K_2O$  with respect to  $Na_2O$  in 110 precisely monitored analyses of Australasian tektites. Thirty-four analyses by Schnetzler, open circles; 43 by Sachs, black circles; 16 by Carron and Cuttitta and 3 by Elmore, Barlow, Botts, and Chloe, open squares; and 14 by Martinec, black squares. Dashed lines mark range of k-value and of total alkali oxide.

obsidians from a given source (Hamilton, 1963; Anderson, 1933). Total alkali oxide ranges from 2.92 (javanite) to 4.45 (high alumina australite) and averages 3.62 percent. These ranges and average total alkali are almost identical with those of 21 bediasites (representing a wide compositional range based on specific gravities and refractive indices; Cuttitta and others, 1962; Chao, 1963) in which the k-values range from 0.43 to 0.50 and average 0.47. Total alkali oxide ranges from 2.88 to 4.27 and averages 3.62 percent. The remarkably similar alkali characteristics of bediasites and Australasian tektites strongly suggest a similar genesis and, because of the narrow range in alkali ratio, render derivation from any but an igneous source highly improbable. Conversely, given a similar genesis, the modern alkali analyses of both bediasites and Australasian tektites suggest high analytical precision.

In contrast to the modern, precisely monitored analyses, the 55 older alkali analyses might well be used to support a sedimentary derivation for tektites; the wide range in both ratio and total alkali are more nearly characteristic of thick units of clastic sediments (Reed, 1957; Bailey and others, in press) than of igneous rocks. Figure 2 shows the variation of  $K_2O$  with respect to  $Na_2O$  for the older analyses; 28 of the 55 points fall outside the superimposed field of modern analyses (fig. 1). The k-values range from 0.39 to 0.66 and average 0.49, indicating a slight bias in favor of  $Na_2O$  relative to the modern analyses. Total alkali oxide ranges from 2.16 to 5.21 percent--twice the range of the

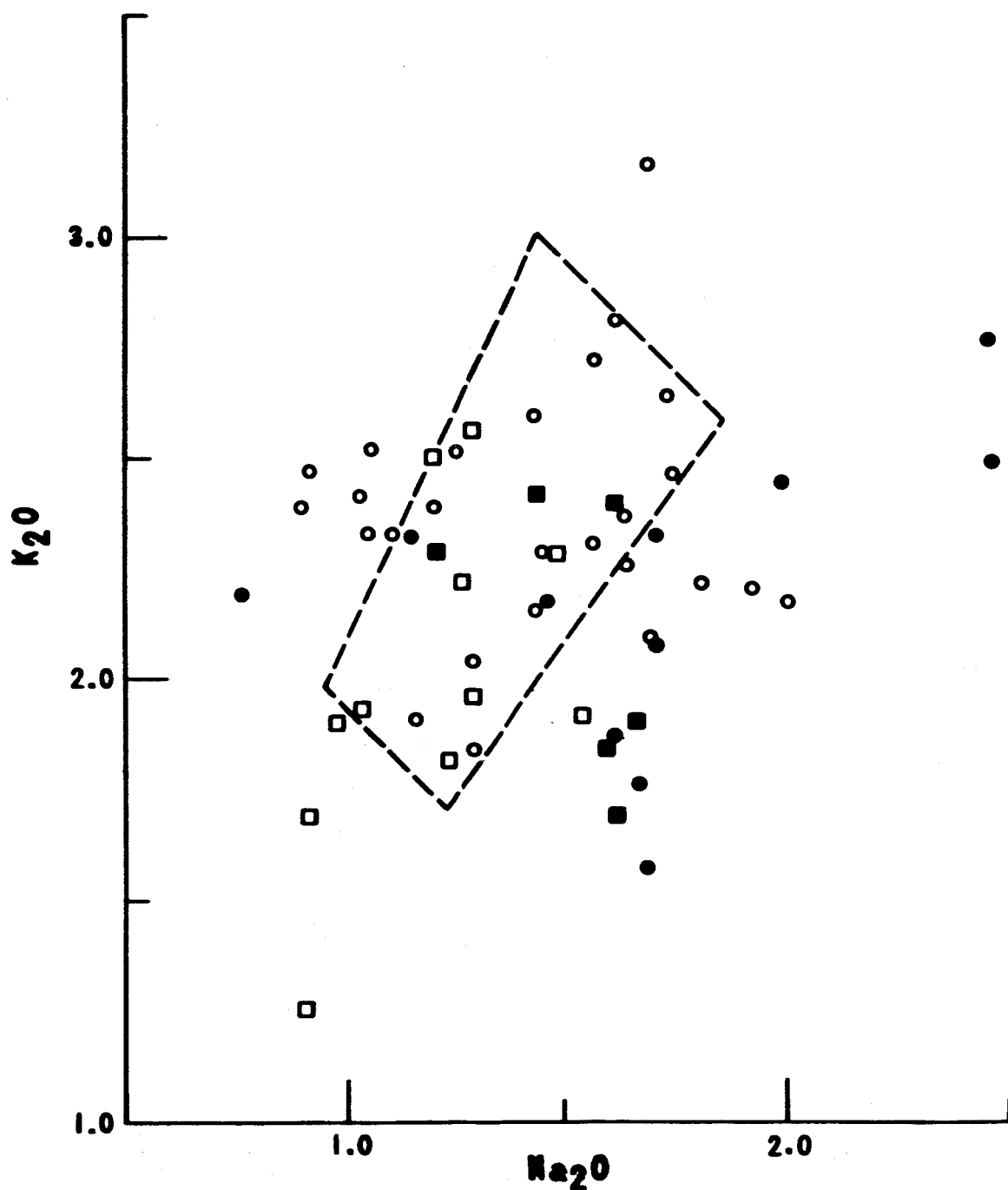


Figure 2. Variation of  $K_2O$  with respect to  $Na_2O$  in 55 older analyses of Australasian tektites. Twenty-four Indochinites, open circles; 10 Javanites, 2 Borneo, and 2 Malay, black circles; 11 Australites, open squares; and 6 Philippinites, black squares. Dashed lines mark field of precisely monitored analyses of figure 1.

modern analyses. The average total alkali oxide, however, is 3.68 percent, strikingly close to the 3.62 percent total alkali oxide of the modern analyses despite the wide spread in the older analyses.

That the precision and accuracy of the older alkali analyses of tektites are indeed suspect, and yet of a quality about average for alkali analyses before precise monitoring, is strongly suggested by comparing figures 1 and 2 with figure 3, which shows the variation of  $K_2O$  with respect to  $Na_2O$  for 60 early analyses of G-1 granite and 59 of W-1 diabase (Schlecht and Stevens, 1951; and Stevens and Niles, 1960). Nineteen of 60 G-1 analyses and 22 of 59 W-1 analyses fall outside the rather generous adopted limits of acceptability (mean  $\pm$  standard deviation) as outlined by the dashed rectangles of figure 3.

Titania determinations in the older tektite analyses also fare badly in light of the modern analyses. Figure 4 shows the decidedly positive correlation of  $TiO_2$  with respect to  $Al_2O_3$  in 98 modern analyses. In contrast, figure 5 shows the same plot for 52 older analyses, only 15 of which fall in the "maximum field" of the modern analyses; moreover, half of the old analyses show a  $TiO_2$  content greater than the highest  $TiO_2$  reported in 110 modern analyses. The  $TiO_2$  of the modern analyses averages 0.71 and ranges from 0.42 to 0.90 percent; in the old analyses it averages 0.84 and ranges from a trace to 1.10 percent. For comparison, 60 early analyses of  $TiO_2$  in W-1 average 1.07 percent, range from 0.10 to 1.68 percent, and have a standard deviation of 0.20.

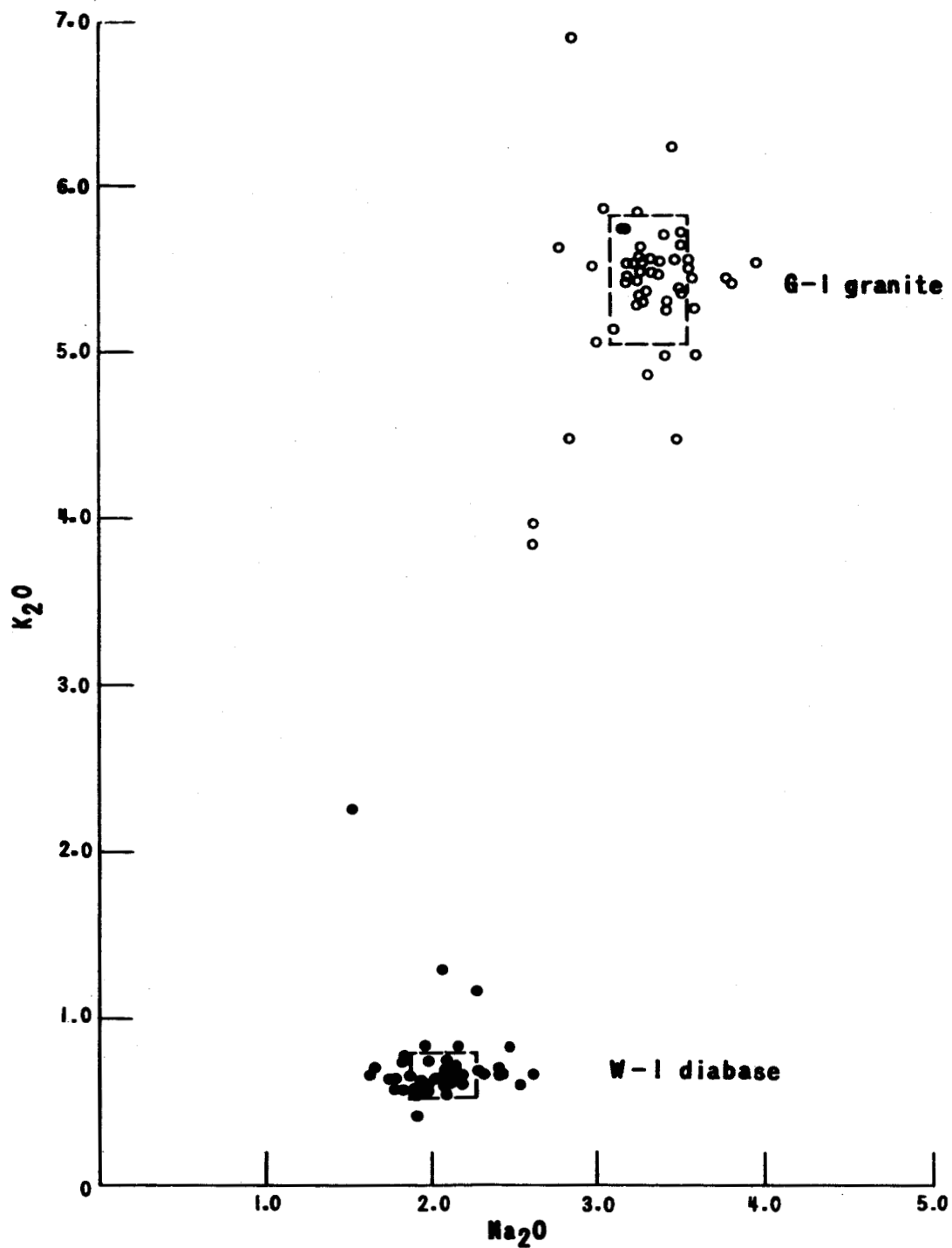


Figure 3. Variation of  $K_2O$  with respect to  $Na_2O$  in 60 early analyses of G-1 granite and 59 of W-1 diabase.

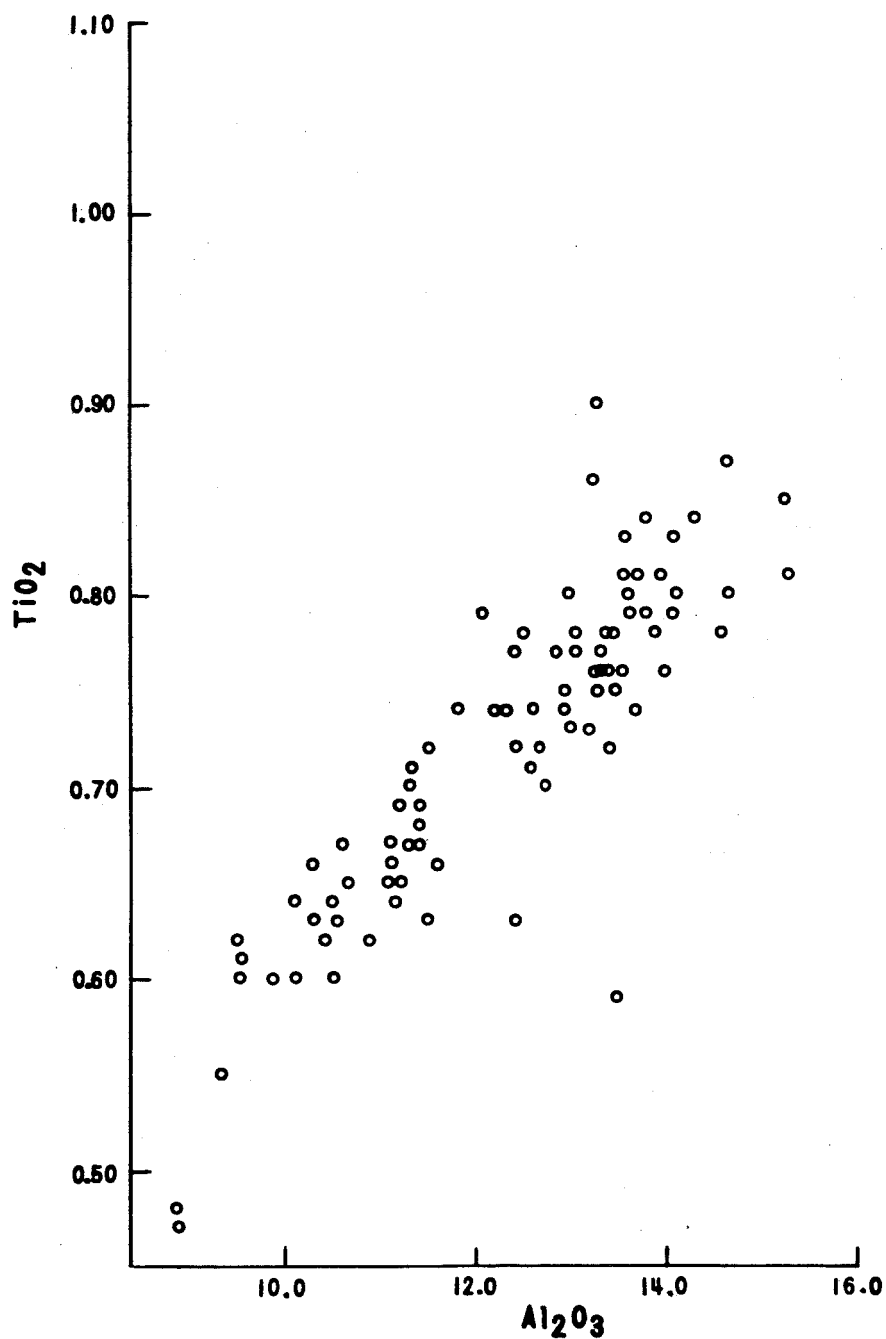


Figure 4. Variation of  $\text{TiO}_2$  with respect to  $\text{Al}_2\text{O}_3$  in 98 precisely monitored analyses of Australasian tektites.



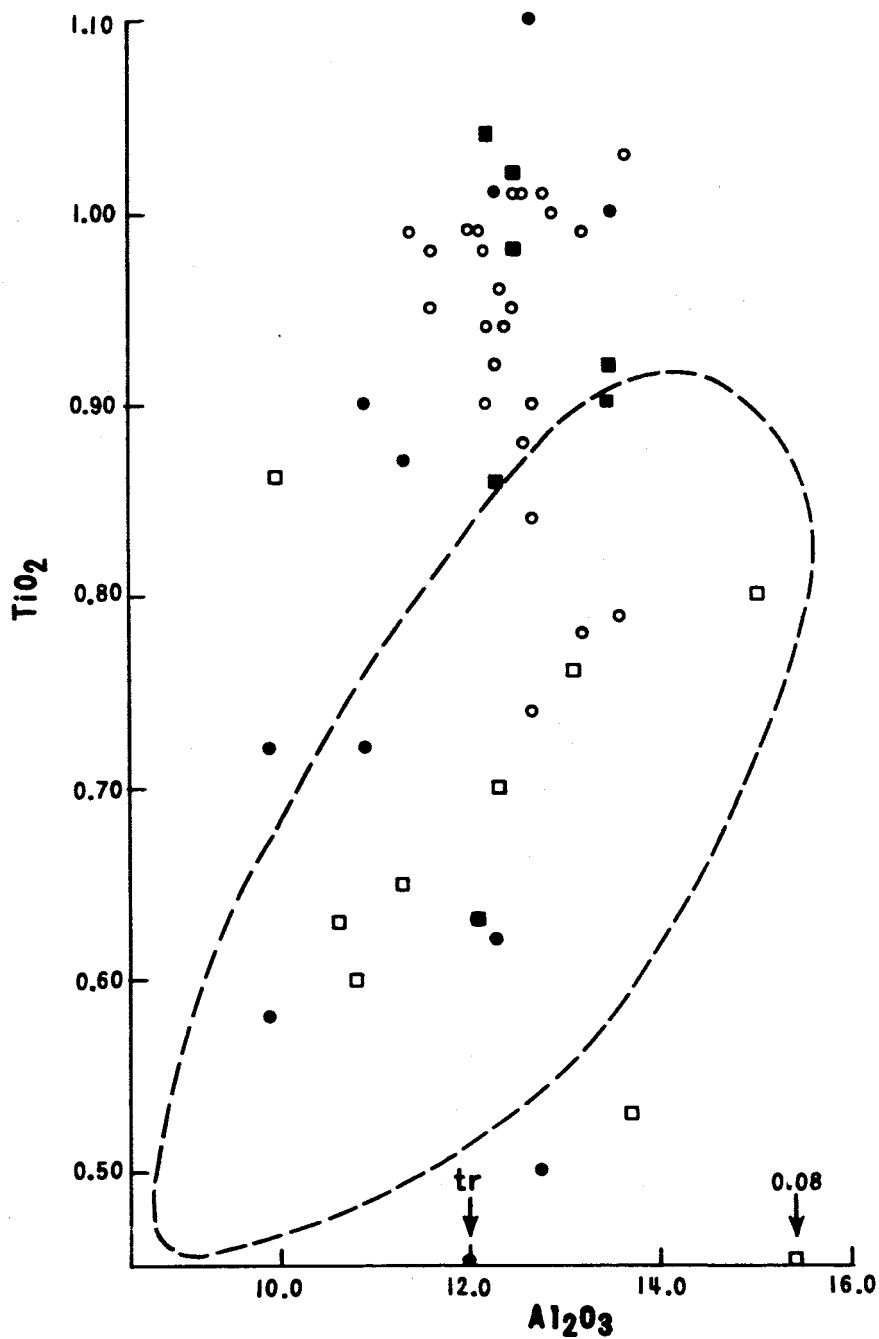


Figure 5. Variation of  $\text{TiO}_2$  with respect to  $\text{Al}_2\text{O}_3$  in 52 older analyses of Australasian tektites. Symbols the same as in figure 2. Dashed line marks field of precisely monitored analyses of figure 4.

In summary, inaccuracies in  $K_2O$ ,  $Na_2O$ ,  $CaO$ ,  $MgO$ , and  $TiO_2$  determinations in the 55 older analyses of Australasian tektites are sufficient to negate any reasonable petrochemical classification on which hypotheses of derivation might be based. The analyses should not be used. Furthermore, a comparison of the older analyses of Australasian tektites with early analyses of G-1 and W-1 suggests that at least a third of pre-G-1 alkali and titania analyses, such as those of Washington's tables (1917), are probably inaccurate. Indeed, it is probable that the agreement between natural and experimental systems in which the alkalis play a paramount role (Tuttle and Bowen, 1958, p. 77-79) is considerably better than analyses from Washington's tables would suggest. Similarly, one might question the use of older titania analyses in petrologic classification (Chayes, 1964), especially in light of comparisons of old and new Hawaiian basalt analyses (MacDonald and Katsura, 1964, p. 102) which suggest the  $TiO_2$  of many of the old analyses is much too high.

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Geophys. Union Trans., v. 45, p. 82.

# LUMINESCENCE OF ENSTATITE ACHONDRITE METEORITES

by M. B. Duke and B. A. Tryba<sup>1/</sup>

## Introduction

Reports of lunar red luminescence (Kopal and Rackham, 1963) have led to an experimental investigation of the luminescence of meteoritic material (Derham and Geake, 1964; Derham and others, 1964). The enstatite achondrites were found to exhibit red and minor blue luminescence. Derham and others (1964) identified the luminescing mineral responsible for both the red and blue luminescence as enstatite ( $\text{MgSiO}_3$ ) and suggested that the red luminescence is due to activation by small amounts of Mn. In many enstatite chondrites and enstatite achondrites Keil (oral communication) has observed red- and blue-luminescing enstatite excited by 20 KeV electrons in an electron-probe analyzer.

We have made two simple experiments that bear on the problem of meteorite luminescence. First, we separated a mineral from the Norton County meteorite that luminesces red under ultraviolet radiation, and found it to be forsterite ( $\text{Mg}_2\text{SiO}_4$ ), not enstatite. Although this is apparently in disagreement with the data cited above, the differences in luminescence may reflect the different manner in which luminescence was excited in the two experiments. Second, we observed the luminescence of artificial

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diopside ( $\text{CaMgSi}_2\text{O}_6$ ), containing small amounts of Mn, Ti, Ni, Cr, and Fe, estimated by irradiation with 30 KeV electrons in an electron-probe analyzer. Pure diopside luminesces blue while Mn-bearing diopside luminesces red, which possibly explains the previous observations of red- and blue-luminescing enstatite in the Bustee meteorite (Derham and others, 1964) if the Mn content of the enstatite is variable.

#### Red luminescence in the Norton County meteorite

Red-luminescing grains up to 5 mm in diameter were separated by hand picking from a sample of the Norton County meteorite, after irradiation by long wavelength (3650 Å) UV radiation. X-ray diffraction powder patterns taken of the luminescing material showed only the lines of forsterite ( $\text{Mg}_2\text{SiO}_4$ ), whereas patterns taken of non-luminescing grains in the meteorite sample showed only the lines of enstatite ( $\text{MgSiO}_3$ ). Emission spectrographic analyses show that the Mn content of the enstatite is 500 ppm and that of the forsterite is 400 ppm.

Reported forsterite contents in the enstatite achondrite meteorites range from 0.5 percent to 5.0 percent (Foshag, 1940; Lonsdale, 1947). The approximate content of luminescent forsterite in about five grams of Norton County fragments is 3 percent.

### Electron excitation of synthetic diopside

A suite of synthetic diopsides, synthesized by Coleman (1962), with small amounts (1 to 5 percent) of usually minor elements, were irradiated with 30 KeV electrons in an electron-probe analyzer. Pure diopside luminesced blue, Mn-bearing diopside, red, Ni-bearing diopside, green, Ti-bearing diopside, orange; Cr- and Fe-bearing diopside showed no luminescence. The amount of luminescence increased with increasing content of the minor elements.

### Discussion

Leverenz (1944) indicated that complete substitution of Mg for Zn in  $\text{Zn}_2\text{SiO}_4$ , activated by Mn, gives a deep red-emitting phosphor. Garlick (1964) suggested that enstatite ( $\text{MgSiO}_3$ ) activated by Mn might give a red emission. Synthetic diopside containing Mn luminesces red under electron excitation. Although the spectrographic analyses for Mn in Norton County forsterite show a fairly low Mn content, it seems probable that it is indeed Mn that activates the luminescence.

Our experiment shows that under UV radiation, forsterite is a much more efficient emitter than enstatite and must contribute most of the luminescence of the total meteorite sample. Even assuming an unusually high efficiency of 50 percent for the forsterite, the resulting luminescent efficiency for the whole meteorite would be only on the order of 1 to 2 percent. This low



efficiency is similar to that suggested by Derham and others and indicates that red lunar luminescence is not likely to be caused by luminescence of enstatite achondrite material. It does not appear possible that silicate rocks, even with concentrations of high luminescing minerals can provide total luminescent efficiencies sufficient for significant lunar luminescence.

The electron-probe observations of luminescence of diopside are perhaps applicable to the explanation of the blue luminescence of part of the enstatite of Norton County. If there is a variation of Mn content, the luminescence may vary from grain to grain. Different Mn contents of two distinct types of enstatite, distinguished as "glassy" and "cleavage" enstatite (Beck and LaPaz, 1951), may lead to the observed blue and red luminescence.

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## ERRATA SHEET

### PART C: COSMIC CHEMISTRY AND PETROLOGY

#### ANNUAL PROGRESS REPORT

July 1, 1963 to July 1, 1964

Page 4 caption should read;

Figure 1. Comparison of spalled moldavite teardrop from Slavice, Moravia (a) with spalled australite teardrop from Renmark, South Australia (b). Upper right--posterior view; upper left--anterior view; lower left--side view with posterior side to the right; and lower right--side view with posterior side to the left.

Page 50 caption should read;

Figure 23. Photograph showing the gently dipping surface of the northwestern rim of the Sangiran Dome at triangulation station no. 356, 6 miles north of Surakarta, Java. The surface was underlain by an unstratified lag gravel as shown by the T-shaped trench. Some 300 javanites were reportedly found on top of this surface. None were found within the lag gravel.

Page 51 caption should read;

Figure 22. Geologic cross section showing the thin layer of unstratified lag gravel overlying the Middle Pleistocene Kabuh beds.

Page 89 caption should read;

Figure 1. Analytical curve for the determination of K in 3.97 perchloric acid solutions of silicate rocks using the rotating disc-high voltage spark method. Percent values refer to the K content of the original silicate rock.

Page 90 caption should read;

Figure 2. Analytical curve for the determination of Na in 3.97 perchloric acid solution of silicate rocks using the rotating disc-high voltage spark method. Percent values refer to the Na content of the original silicate rock.